SOVIET AIRCRAFT AND ROCKETS

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Published for the
National Aeronautics and Space Administration, and
the National Science Foundation, Washington, D.C.
by Amerind Publishing Co. Pvt. Ltd., New Delhi

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TT 74-52007
NASA TT F-770

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(ZNAKOM'TES', SAMOLET I RAKETA)

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Transport Publishers
Moscow, 1971

Translated from Russian

Published for the
National Aeronautics and Space Administration, and
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by Amerind Publishing Co. Pvt. Ltd., New Delhi
1977

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*Translated and Published for the National Aeronautics and
Space Administration, pursuant to an agreement with
the National Science Foundation, Washington, D.C.
by Amerind Publishing Co. Pvt. Ltd.,
66 Janpath, New Delhi 110001*

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*Available from the U.S. Department of Commerce
National Technical Information Service
Springfield, Virginia 22161*

*Printed at Oxonian Press Pvt. Ltd., Faridabad, India
Production: M.L. Gidwani*

How are modern aircraft, helicopters, multi-stage rockets constructed? What keeps them in the air? What kind of engines are used in flight vehicles, how are they built? What instruments are installed in aircraft to control apparatus, systems and flight? In this book the reader will find answers to all these questions along with many others.

This book is based on material from Soviet and foreign publications. It is meant for a variety of readers who have an interest in aviation and cosmonautics.

Contents

SECTION ONE

In Herculean Flight

AT THE OUTSET OF AVIATION

Young man! Ours is the age of intent study of the sky, as was said by the great scientist and thinker K.E. Tsiolkovskii. If you carry deep in your heart the ardent, cherished dreams of aviation, of cosmonautics, if the sky insistently calls you, then fling open the doors of the aviation school.

Our motherland needs thousands of young enthusiasts of the sky striving to master the very complex techniques of modern aviation which require not only determined will and physical hardiness but also profound, many-sided knowledge.

The sky always liked courageous young men.

Don't you want to follow in the footsteps of Chkalov, Gromov, Pokrishkin, Kozhedub?

Don't you want to become a member of the great, heroic family of flyers who leave the trails of their supersonic machines in the blue of the sky? Don't you want to bring about mankind's daring dream of conquering the cosmos and its interstellar spaces?

There are peaks in the deeds of human genius and one peak was the first triumphant space flight of Soviet cosmonaut Yuri Gagarin.

He was the first in the world to dare to enter the uncertainty of barren space and to accomplish the deed.

Deed...What a beautiful, exalted, meaningful word! The deeds of Soviet patriots are countless. They are like a mosaic of thousands of pieces forming a grand picture of heroism in war, which is the great symbol of the deeds of our people.

At the time of the Great Patriotic War our motherland crowned more than 11,000 of her best sons with the high title of Hero of the Soviet Union.

In everyone of their deeds the gallant features and moral qualities of a citizen of the Soviet Union shine forth. The man of the deed lives in the heart of the motherland, his deed—the fire in the human heart—is immortal.

In the field of unflagging peaceful creativity that changes the face of a country our motherland has come to occupy the front rank in the world's achievements in science and led the world to a new social plane.

Our great power is in mighty flight. Its days are filled with the inspiration of a nation building communism.

The achievements of our country's millions are inseparably linked with the name of one whom the whole proletarian world carries in its heart, one with whose name is linked our stormy and momentous era, one who "with his intellect pierced through the limits of centuries." This great name is Lenin.

* * *

For many centuries past man, awed and puzzled, has fixed his gaze on the mysterious abyss of the sky. Many poetic legends survive in different countries concerning man's striving for flight. One of them is the legend of Icarus and Daedalus.

The ancient Greek artist and sculptor who was a prisoner on the island of Crete together with his son Icarus constructed wings for flight and fastened them with wax. They wanted to fly away from their prison. Before the flight Daedalus warned his son not to fly very high because the hot sun might melt the wax on the wings.

But when he rose into the sky Icarus felt so delighted and happy that he rushed up to the chariot of the sun god Helios. The wax on the wings melted and Icarus fell to the rocky shore below.

In Tsarist Russia the genius M.V. Lomonosov was one of the first scientists to prove the possibility of flight by a heavier-than-air machine. In the summer of 1754 at a meeting of Russian scientists in the conference hall of the Russian Academy of Sciences, Petersburg, he demonstrated his heavier-than-air flying model.

A.F. Mozhaiskii, who for many years studied the flight of birds, is rightly considered to be the originator of the first aircraft in the world. Many a time he rose into the sky in a glider, driving it at high speed against the wind with the help of a troika.*

Eighteen hundred and seventy-seven. On the premises of a manoge† in Petersburg, before a large audience, A.F. Mozhaiskii tested his flying apparatus—a model airplane propelled by three propellers turned by clockwork. A committee one of whose members was the famous scientist D.I. Mendeleev thereupon approved a project to build a full-scale airplane.

*Three horses harnessed abreast.
†Riding-school (French).

Having suffered great material difficulties the stubborn inventor got down to constructing his first aircraft. In the summer of 1882 the aircraft was constructed and tested. During the tests the aircraft climbed into the air. It was the first flight in the world of a heavier-than-air machine.

Aleksandr Fedorovich Mozhaiskii.

In 1884 Konstantin Eduardovich Tsiolkovskii, a humble teacher from Kaluga, began to study the problem of "flight by means of wings." He was an original thinker and great scientist who devoted his long creative life to serving mankind. For the first time (in 1903) he scientifically substantiated the possibility not only of interplanetary but also of interstellar flights.

In donating his numerous books and manuscripts to the Communist Party, K.E. Tsiolkovskii left behind a huge scientific heritage. He was responsible for the project of an original streamlined monoplane that has a fair resemblance to modern machines. His free-wing monoplane was 30 years ahead of its time. In 1894 the project and all the calculations of the machine were published by K.E. Tsiolkovskii in his book *Airplane or Bird-simulated (aviation) Flying Machine*. The Russian Academy of Sciences pronounced favorably on the large flying model of the aircraft but the Tsar's bureaucrats refused help to the inventor. His numerous original works in the field of cosmonautics and the rich mine of his ideas were later widely used to great effect by Soviet scientists.

At the time of the conception of the Russian aviation, Nikolai Yegorovich Zhukovskii, "the father of Russian aviation," as he was called by V.I. Lenin, began his career. This highly talented scientist wrote more than 200 scientific treatises. The activities of N.Y. Zhukovskii were unusually wide and diverse.

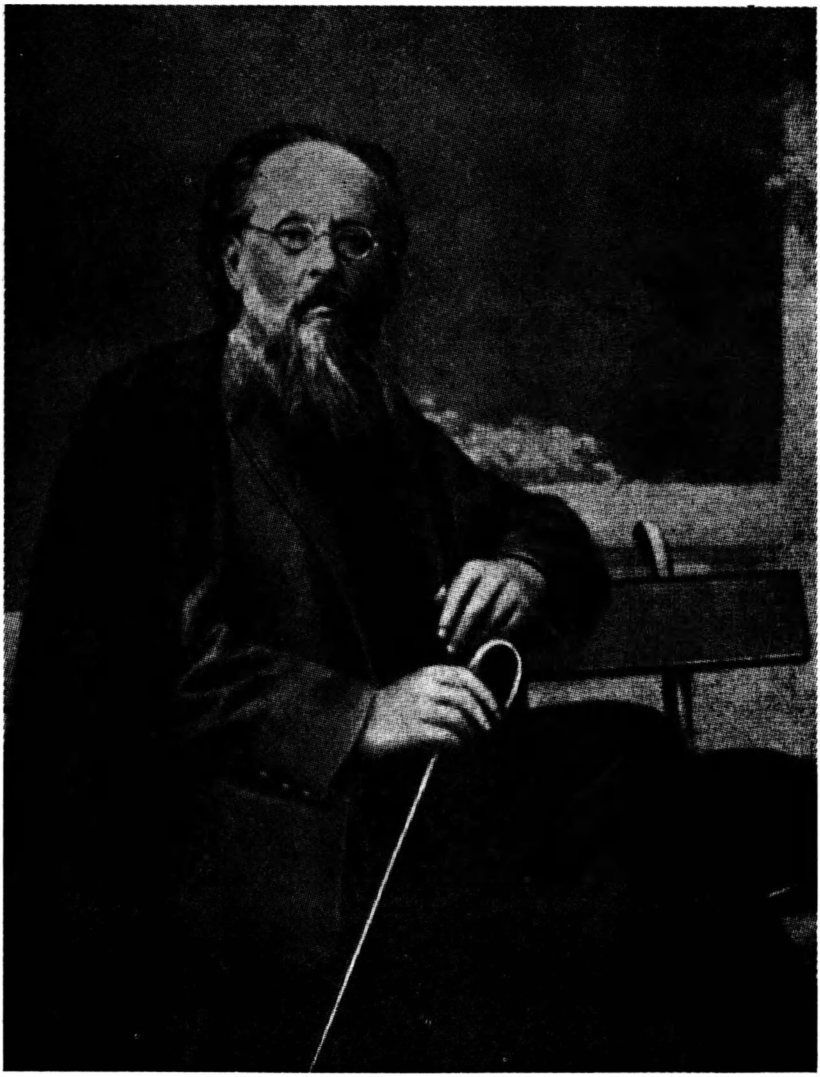
A new method of investigating technical problems combining empirical and mathematical solutions to practical problems devised by Zhukovskii became the order of the day in the science of Russian aviation.

N.Y. Zhukovskii trained up a brilliant galaxy of talented scientists and technicians like S.A. Chaplygin, A.N. Tupolyev, A.A. Arkhangelskii, V.P. Vetchinkin and others.

A co-worker of N.Y. Zhukovskii's and an outstanding scientist,

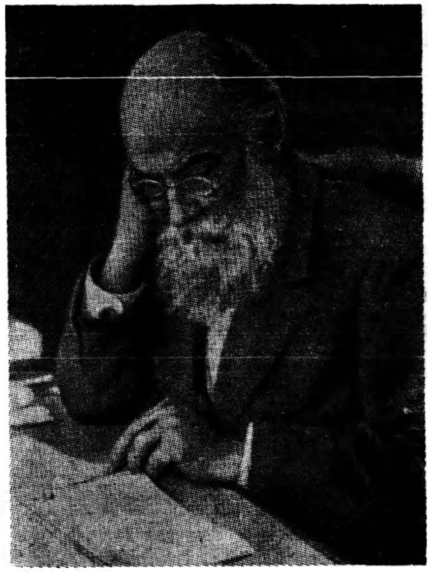
S.A. Chaplygin, earned a worldwide reputation in aviation circles with his work *On Gas Jets,* launching a new branch of science—gas dynamics.

One of the pioneers of aviation, A.A. Porokhovschikov built his first aircraft, the P-1, while still young. It developed a speed of 90 kmph and was approved by N.Y. Zhukovskii. The second aircraft he built, the P-2, had a speed of 110 kmph. It had a machine-gun mounting and a device for dropping bombs.



Konstantin Eduardovich Tsiolkovskii.

Porokhovschikov also built the world's first prototype of an attack aircraft, the BI-KOK-2. He then constructed the fighter aircraft P-3, the two-seater trainers P-4 and P-6-bis, and a two-seater fighter aircraft, the P-5.



Nikolai Egorovich Zhukovskii.

The pioneer pilot and founder of aerobatics, Pyolr Nikolayevich Nesterov, added a glorious chapter to aviation in our motherland.

On August 27, 1913, this courageous pilot, for the first time in the world, performed the "death loop." As is well known, the modern dogfight is unthinkable without the knowledge of flight maneuvers. Nesterov performed his final, immortal deed in the First World War on August 26, 1914. During a dogfight he rammed an Austrian three-seater *Albatross*. The enemy aircraft plunged to earth...but our courageous pilot was also killed in the action.

Sergei Alekseevich Chaplygin.

In the stifling, moldy atmosphere of Tsarist Russia many aviation enthusiasts continued to work. They constructed interesting aircraft for the time. In Petersburg the talented technician-engineer Y.M. Gyekkyel built nine aircraft of his own design; in Kiev, D.P. Grigorovich and other constructors achieved indubitable success in building airplanes; in Kharkov, S.V. Grizodubov built two aircraft of his own design; in the Caucasus, the famous pilot A.V. Shiukov built his aircraft and gliders.

A highly gifted inventor, A.G. Ufimtsev, built a radial engine and a "spheroplane" in Kyrsk.

In 1913 a group of designers under the guidance of V.A. Slyesaryeb constructed a huge aircraft, the *Svyatogor*, with two engines of 450 hp, a

wing area of 180 m² and payload of 6.5 tons. V.A. Slyesaryev took part in building another big aircraft, the *Russkii Vityaz*. Carrying seven passengers, this aircraft developed a speed of 90 kmph. It set a world record for long-distance flight. At the end of 1913 after putting the finishing touches to the *Russkii Vityaz* the Russian engineers built another giant aircraft, the *Ilya Muromets*, with an all-up weight of 4,800 kg and during the winter of 1914 conducted flight tests. The aircraft mounted one cannon and eight machine-guns. It was accepted as a weapon by the Russian army.

Founder of Aerobatics P.N. Nesterov.

LENIN AND SOVIET AVIATION

A leader and thinker of genius, V.I. Lenin while in exile took a deep interest in the exploits of flying machines.

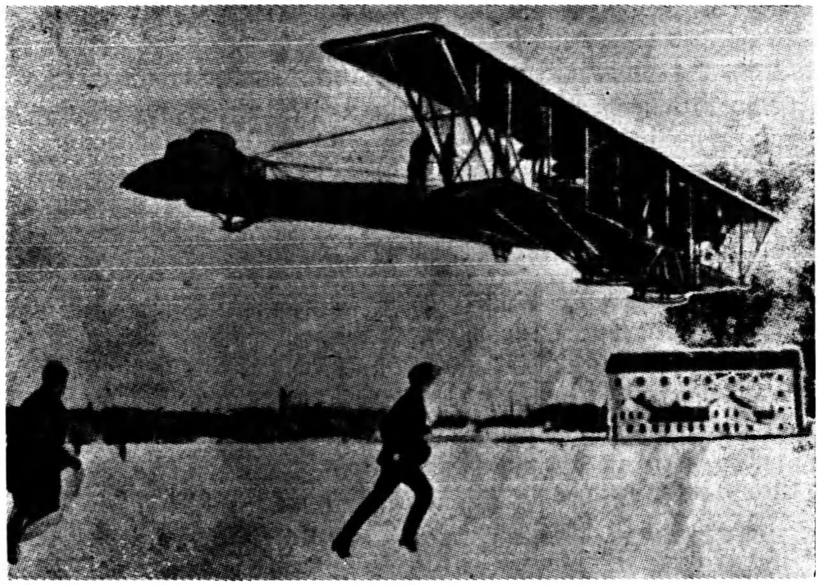
In a draft speech prepared for an address by Bolshevik-deputy G.I. Petrovskii in Dum in 1914 Vladimir Ilyich Lenin indicated that the rise of aviation heralded the "age of airplanes." In another work, "*The Break-up of the II International*" (1915), V.I. Lenin emphasized that aviation was necessary in order to ensure the flexibility and mobility of the army and that aviation could increase the strike power of the army tens of kilometers deep inside enemy territory.

The Great October Revolution came. From the very first steps in the building of Soviet power V.I. Lenin began to pay more attention to Soviet science, specifically to the development of aviation. On the second day of the October uprising he decided to use aviation to drop leaflets behind enemy lines as well as for communications. On October 28, 1917, he gave instructions for the use of the detachment of the air force stationed near Petrograd against General Krasnov's troops.

In November, 1917, the first revolutionary aviation control headquarters was organized in Smolny. It was the bureau of commissars of aviation and flying attached to the revolutionary-military committee headed by A.V. Mozhayev. It proved indefatigable in forming air force detachments and preparing pilots devoted to the revolution.

In December, 1917, on Vladimir Ilyich Lenin's instructions the All-Russian Board of Republican Air Force Control was established. The

Board's task was to form air force detachments, to direct them, to collect and preserve aviation hardware and to select personnel.



The aircraft "Ilya Muromets" landing.

V.I. Lenin kept a watchful eye on the optimum use of aviation in the difficult struggle with numerous enemies. Archives show that a considerable number of resolutions connected with aviation questions were passed by the Council of Labor and Defense in the years 1918–19. Many of them are signed by V.I. Lenin.

By the end of 1917 the first six air force detachments had been formed in the Petrograd military command. Such organizing also began in other towns.

Private aircraft plants and workshops were nationalized; measures were taken to prepare flight personnel from among communists in the Petrograd and the Moscow schools of aviation.

In May of 1918 the All-Russian Board of Republican Air Force Control was abolished. All the air forces of the Republic were to come under the Main Board of the Workers' and Farmers' Red Air Force (Glavvozdukhflot).

In September an aviation and flight field control, "Aviadarm," headed by A.V. Sergyeyev, was set up.

In 1919, on the initiative of the Central Committee, the RKP (b) Heavy Aviation Commission was set up with N.Y. Zhukovskii as chairman.

Under his guidance a team of scientists, engineers and designers began to work on the project of the twin-engine triplane *KOMTA*.

V.I. Lenin followed every step in the development of aviation with great attention and encouraged the growth of aircraft production in all ways.

In spite of the difficult conditions in the country, the devastation and hunger, V.I. Lenin signed the protocol of the Conference of the Soviet of People's Commissars, releasing resources for the modernization of aircraft production plants. In 1921 gold worth three million roubles was allocated.

During the civil war the country's aviation plants repaired 1,574 aircraft and 1,740 engines and also manufactured 750 new aircraft and more than 200 engines.

In close collaboration with Main Air Force Control (Glavvozdukhflot) V.I. Lenin guided the use of aviation on all the war fronts. Specifically he proposed to use aircraft in the war against enemy cavalry. The Red pilots executed the most diverse battle tasks: they carried out air reconnaissance, located enemy reserves and conducted raids on the batteries. For courage and bravery in battle 219 pilots were honored with the high award of the Order of the Red Banner.

An important document, the decree "on air traffic in the airspace over territory of the RSFSR and its territorial waters" signed by V.I. Lenin on January 17, 1921, laid the foundations of Soviet air law, specified orders and conditions for the use of aviation and established clear-cut rules for flights of foreign aircraft over the territory of our motherland.

In May, 1921, the Moscow-Oryol-Kharkov air link was opened. It operated with the aircraft *Ilya Muromyets.* In 1921 the Soviet Government signed a treaty with Germany to set up the Soviet-German Society of Air Communications, "Dyeruluft." In May, 1922, the first international air route, Moscow-Koenigsberg (Kaliningrad), a distance of 1,300 km, was opened. V.I. Lenin gave instructions to allocate 10 aircraft to this airline. Five Soviet and five German pilots began to fly the Moscow-Orel-Kharkov route. Although there was neither weather bureau nor radio communications our pilots flew strictly according to schedule. Among them N.P. Shebanov, the first pilot in the country to clock 1 million kilometers, was distinguished for his skill.

Almost at the same time as the decree "on air traffic" was signed a decision by the Council of Labor and Defense to set up a committee to work out a program of aeronautics and aircraft construction was approved. These Lenin documents were of great significance for the foundation of Soviet aviation.

M.I. Kalinin was profoundly correct when he wrote, "All who are proud of our air fleet, all to whom it is dear, remember that our Ilyich watched over its cradle."

THE WINGS OF THE MOTHERLAND ARE STRENGTHENED

In the spring of 1923 the All-Russian Air Fleet Friends' Society (ODVF) was organized to help in the formation of an air fleet. The affiliated societies "Dobrolet," "Ukrvozdukhpum'" and "Zakavio" were formed to develop a civil air fleet.

In December, 1918, on the instructions of the central committee of the party and V.I. Lenin, the Central Aero-Hydrodynamic Institute (*TsAGI*) had been organized. It later became one of the world's outstanding scientific research centers in the field of aviation.

In 1922 a team of designers under the guidance of A.N. Tupolev built the ANT–1 aircraft. On the basis of this aircraft the first all-metal aircraft, the ANT–2 (made of duralamin smelted in the Kolchugin plant), was designed and constructed. The next all-metal aircraft, the ANT–3 (R–3), with a 400 hp engine, went into assembly line production and was adopted by the air force (VVS). In 1926 test pilot M.M. Gromov performed a magnificent high-speed flight over European capitals in an aircraft of this type named *Proletarii*.

Hero of the Soviet Union
V.P. Chkalov.

In November, 1925, a heavy bomber, the ANT–4 (TB–1), one of the biggest aircraft in the world, was built. It set several world records for long-distance flight with cargo. Building of the ANT–4 was a remarkable achievement on the part of Soviet aircraft construction. For many years it determined the direction of the development of heavy aircraft construction, not only in the Soviet Union but also abroad.

An all-metal nine-passenger aircraft, the PS–9 (ANT–9), was introduced in the airline around May, 1929. It successfully operated together with the eight-passenger aircraft K–5 designed by K.A. Kalinin.

The civil air fleet expanded at a rapid rate during the Soviet Five-Year Plans. In 1928 its aircraft flew 36 times as many kilometers as in 1923. The network of air routes was enlarged. The indigenously built aircraft flying these air routes were in no way inferior in flight performance to their

best foreign counterparts. For example, the production aircraft R–5 of N.N. Polikarpov's design (P–5 in the civil version) won first place in a competition at Tehran in 1930.

In September, 1931, an all-metal aircraft, the *Stal–2** of A.I. Putilov's design, with a 300 hp M–26 engine, was released. Carrying five passengers, it had a maximum speed of 200 kmph and a flight endurance of five hours.

The engineers of the Kharkov Aviation Institute constructed an aircraft designated the KhAI–1. Thanks to its clean lines the aircraft developed a speed of 300 kmph, then a world record.

At the beginning of the thirties a heavy four-engine bomber, the ANT–6 (TB–3), was released for flight testing by A.N. Tupolev's design bureau. With the construction of the ANT–6 began the large-scale production of heavy aircraft in our country. The TB–3 was adopted by the air force (VVS). Its flight performance long remained unmatched.

These aircraft landed at the North Pole and took part in many expeditions.

The experience gained in building the ANT–6 helped A.N. Tupolev's team in the construction of a huge 36–passenger aircraft, the ANT–14 *Pravda*, which was used for about 10 years by the airlines.

Hero of the Soviet Union
M.M. Gromov.

In 1934, A.N. Tupolev's team built the giant-engine aircraft ANT–20, named *Maxim Gorky* in commemoration of the great writer's anniversary. It had a wing span of 63 m, weight of 53 tons and flight ceiling of 6,000 meters. It was 72–passenger aircraft, equipped with a printing press, an automatic telephone exchange for 16 telephones, a cinema unit, etc.

In 1933 the ANT–25 aircraft with an exceptional wing-span 2.5 times the length of the fuselage, was commissioned. In September, 1934, M.M. Gromov, I.T. Spirin and A.I. Filin set up a world record for endurance and range by flying this aircraft 12,411 km in 75 hours on a closed circuit over the USSR. In the summer of 1936 V.P. Chkalov, G.F. Baidukov and A.V. Belyakov flew 9,374 km in 56 hours and 20 minutes on the Moscow-Udd island route. The following year the crew chalked up another record

*Steel–2.

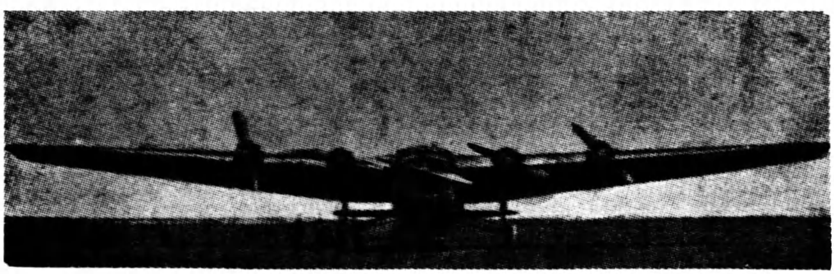
flight: Moscow-North Pole-USA, covering 9,130 km in 63 hours 16 minutes. A crew consisting of M.M. Gromov, A.B. Yumashev and S.A. Danilin. flying the aircraft ANT–25, set up an all-new range record by covering the distance from Moscow to San Jasinto (USA) in 62 hours and 17 minutes. They flew 11,500 km, the distance in a straight line being 10,148 km.

These remarkable flights showed the whole world that Soviet aviation was spreading its mighty wings wider and wider. The total length of air routes in the USSR was considerably increased. Around the beginning of 1939 it had grown to 138,000 kilometers. Freight traffic increased more than 10 times. Agricultural aviation and other specialized aviation brought huge benefits to the country. The flight and technical personnel trained by the Communist Party were increased. The USSR became a leading nation in aviation.

On June 22, 1941, Hitler's Germany treacherously attacked our motherland. In the difficult days of the Great Patriotic War, Soviet pilots, like all soldiers and sailors of the Soviet armed forces, showed high moral and fighting qualities, inflexible will for victory, selflessness and great fighting skill.

The heroic deeds of Captain N.F. Gastello and the crew of his aircraft: Lieutenant A.K. Burdenyuk, Radio Operator G.N. Skorobogatii and Senior Sergeant A.A. Kalinin, found an eternal place in the glorious chronicle of our air force as an example of selfless service to the motherland.

After dropping bombs on enemy tanks Gastello's aircraft turned away from the target, strafing the crews of fascist tanks. Then a shell from the



The aircraft ANT–14 *Pravda*.

fascist side hit Gastello's aircraft. Having received a direct hit, the aircraft was enveloped in flames and was unable to return to base. Captain Gastello then turned the burning aircraft back and dived into the midst of the tanks. A column of fire enveloped the tanks and their fascist crews.

The Soviet Government posthumously conferred on pilot N.F. Gastello the rank of Hero of the Soviet Union.

On the night of August 6, 1941, a young fighter pilot and member of the

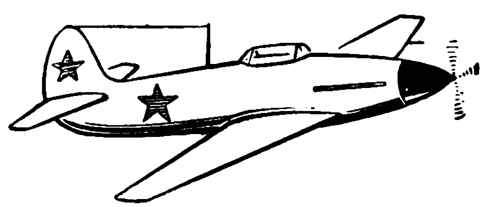
Komsomol*, Viktor Talalikhin, performed his deed over Moscow.

While on patrol V.V. Talalikhin noticed a fascist bomber trying to force its way to the center of Moscow under cover of night. Without delay the pilot attacked the enemy. In the subsequent dogfight V.V. Talalikhin used up all his ammunition. The courageous pilot would not allow the fascist to escape unhurt and decided to ram the intruding bomber. He dived on the enemy and destroyed the enemy bomber's tail with his propeller.

The Soviet pilot and Hero of the Soviet Union Aleksei Petrovich Marecev is widely known in our country. In an ill-matched dogfight his aircraft was put out of action. The heavily injured pilot, his feet shattered, found himself in a dense forest in enemy-occupied territory. For 18 days, living on berries he was luckily able to find under the snow, A.P. Marecev crawled his way to the front. On the nineteenth day the Soviet people saved him from death.

More than 200,000 pilots, navigators, gunners, radio-operators and other airmen were rewarded with orders and medals. The high title of Hero of the Soviet Union was conferred on 2,119 pilots, 69 of whom received the "Zolotaya Zvezda†" with it. Exceptional bravery and skill in air battles were shown by our thrice-decorated Heroes of the Soviet Union, I.N. Kozhedub and A.I. Pokryshkin. Civil aviation, by rendering priceless help to the Soviet army in defeating German fascism, made a big contribution to the country's defense.

During the war aircraft designers were constantly at work on the construction of new aircraft and engines and perfecting their earlier designs taking into account the experience of battle operations.



The fighter plane Yak-9, 1942.

A design bureau guided by S.V. Il'yushin built a new military aircraft, the widely known Soviet attack plane Il–2. Our air force was also equipped with the excellent aircraft of A.S. Yakovlev and S.A. Lovochkin. The fighter planes *Yak* and *La* in many respects surpassed enemy aircraft. Piloting aircraft designed by A.N. Tupolev, Soviet pilots demolished enemy strongholds and destroyed troops and weapons.

*Young Communist League.
†Gold Star.

Aircraft engines and special equipment of Soviet manufacture splendidly withstood the severest test of war.

SOVIET AVIATION AFTER THE PATRIOTIC WAR

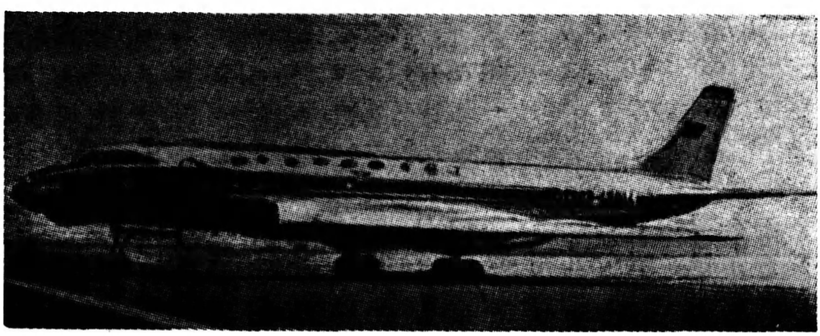
After the destruction of fascism the restoration and construction of new airlines and airports began at a rapid pace.

Already by 1945 the total volume of air transportation in comparison with that in 1940 had almost tripled, the number of passengers carried had increased 1.5 times and the freight and mail 1.2 times. A network of international airlines grew up. Civil aviation was equipped with aircraft of S.V. Il'yushin, the Il–14 and Il–12, O.K. Antonov's An–2 and A.S. Yakovlev's *Yak–12*.

Finding that piston engines did not meet contemporary needs, a team of designers guided by academician A.N. Tupolev built an airliner, the Tu–104, with two turbo-jet engines. On June 17, 1955, pilot Yu.F. Alasheev tested this comfortable machine, which later established 11 world records. In producing the Tu–104 aircraft our motherland was two years ahead of foreign countries in building jet aircraft for passengers.

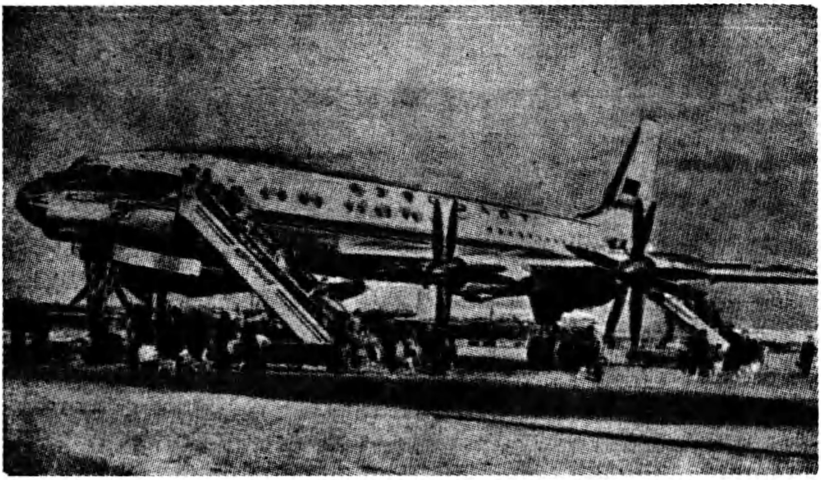
In 1959, the Tu–114 aircraft, with a seating capacity of 220, entered airline service. It set 32 world records. In the world exhibition at Brussels the highest award, the Grant Prix, went to the Tu–114. Twice Hero of Socialistic Labor Academician A.N. Tupolev received the Gold Medal.

In 1958 a turbo-prop passenger aircraft, the An–10, designed by O.K. Antonov, entered airline service. It carries 100 passengers and 3.5 tons of freight and can fly at 600 kmph.



The aircraft Tu–104.

In the same year there appeared S.V. Il'yushin's Il–18 aircraft with four turbo-prop engines giving a speed of 650 kmph and seating capacity for 100.

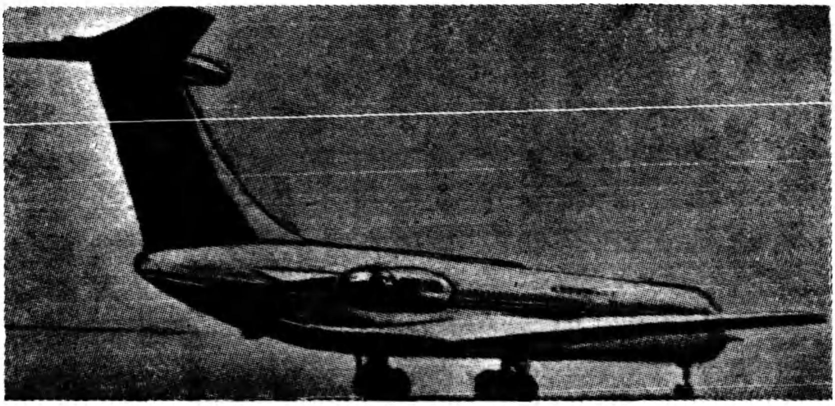


The aircraft Tu–114.

The giant An–22 (*Antei*) aircraft built in 1965 by O.K. Antonov's team of designers is the biggest aircraft in the world (Cabin: 33 meters long, 4.4 meters high) with the biggest carrying capacity (80 tons). The *Antei* has four turbo-prop engines of 15,000 hp each. It is fitted with sophisticated loading and unloading equipment.

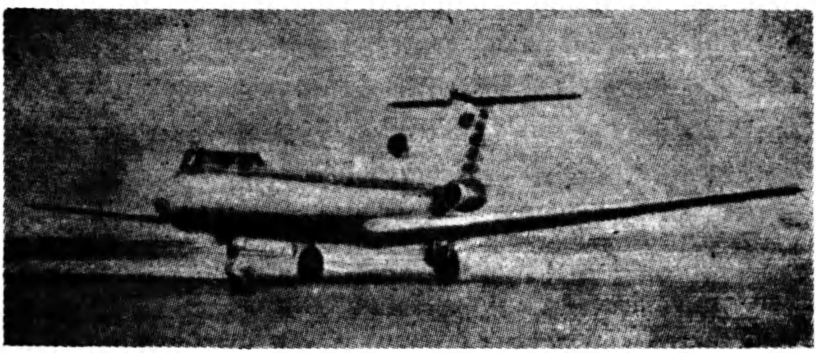
The aircraft Tu–154.

Soon our country's air routes will be served by an excellent comfortable airliner, the Tu–154, which will replace the Tu–104, Il–18 and An–10. Three



The aircraft Il–62.

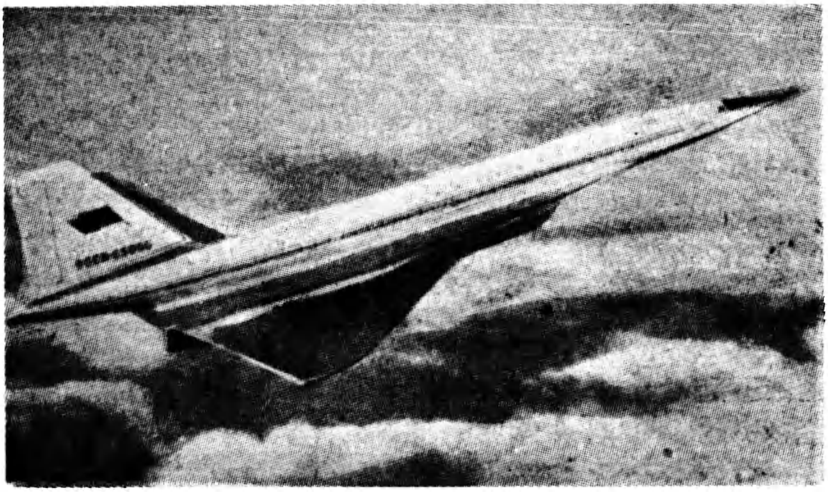
turbo-fan engines located in the tail give the aircraft a speed of 900 kmph. The cabin is designed for 160 passengers but in later modified models it will accommodate up to 250 passengers. The Tu–154 inherits the best qualities of its predecessors: the speed of the Tu–104, the range of the Il–18 and the take-off and landing characteristics of the An–10.



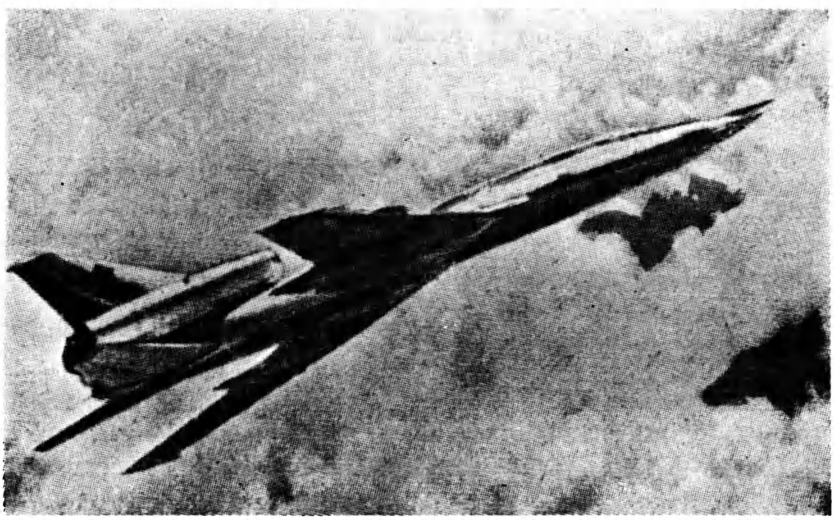
The aircraft Yak–40.

The Il–62, an excellent fast liner designed by S.V. Il'yushin, has begun operating on Aeroflot's transcontinental routes. This intercontinental turbo-jet liner, conceived in S.V. Il'yushin's design bureau, is an outstanding achievement of Soviet aviation science and engineering. Its design has been patented in all the leading industrial countries of the world. It takes on 186 passengers and flies at a speed of 850–900 kmph at an altitude of 10,000 meters.

Notable for its qualities is the jet aircraft *Yak–40* buit by the team of the eminent designer A.S. Yakovlev. It is designed for short take-off and



The supersonic passenger liner Tu–144.



Supersonic missile carrier.

landing from non-concrete runways. The aircraft has three AI–25 engines mounted in the tail and develops a speed of 600–700 kmph. There are 30 seats in the cabin. The ceiling of the machine is 12,000 meters.

On provincial airlines a light passenger aircraft, the Be–30 air microbus, will appear fairly soon. The work of chief constructor G.M. Beriev, it is designed to carry 15 passengers. It will be able to take off from 550–meter

long dirt runways. Two turbo-prop engines will give the machine a speed of 480 kmph.

A supersonic passenger aircraft, the Tu–144, with an in-flight speed of 2,500 kmph, will shortly appear on the air routes. Its range will be 6,500 km, ceiling 20,000 meters and take-off weight 130 tons.

In building the Tu–144 the Soviet Union is opening a new era in the development of world civil aviation, the era of supersonic air communications.

A complex of flying and navigation equipment and the automatic control system installed on board enable the aircraft to fly under difficult weather conditions by day and night. The aircraft will be able to carry passengers from Moscow to the Far East in three hours, to India in two-and-one-half hours and to Paris or London in less than two hours.

Soviet civil aviation serves as a bright example of the great advances

Pilot-astronaut of the Soviet Union Yu.A. Gagarin.

made under socialism. Today it carries up to 25% of the world's air traffic. The total route length of the airways exceeds 650 thousand km, out of which 150 thousand km are international trunk routes covering 60 countries. Every year nearly 75 million passengers utilize Aeroflot's services.

The appearance of our country's air force has undergone a radical change. Today Soviet military aviation has at its disposal the most modern aircraft, from supersonic interceptor aircraft to strategic missile carriers capable of homing on and destroying the enemy in the most remote theaters. Behind the controls of these mighty war machines are the able pilots and navigators who have absorbed the experience of the senior generation of aviators. They are successfully carrying on the tradition.

ON THE WAY TO THE STARS

From the first artificial satellite, from the historic flight of Yurii Alekseevich Gagarin, from Aleksei Arkhipovich Leonov's entry into outer space we have come to a new stage of cosmic research, i.e. the building of permanent orbiting stations and laboratories, toward further development of the systematic study of outer space, the moon and planets of the solar system.

With the positioning of satellites, automatic stations and piloted spaceships in space cosmic research in our country is being developed in three fundamental directions: investigation of near space with the help of satellites, geophysical rockets and spaceships; exploration of the moon and the planets; and medico-biological research together with the flight of men in outer space.

The study of outer space with the help of satellites began on October 4, 1957. In the first stage near space was investigated, the performance of the satellites' systems was studied and the designs of rocket carriers were developed. With the launching of the second artificial satellite, which carried the experimental dog Laika, there began the medico-biological investigations that must precede further developments.

A large number of investigations of varied nature were carried out with the launching of unmanned orbital space ships, the satellites. They helped scientists and designers to prepare for the first human flight in the cosmos. With the help of these satellites the design of spaceships was being worked out along with the testing of life support systems and equipment for returning the spaceship to earth.

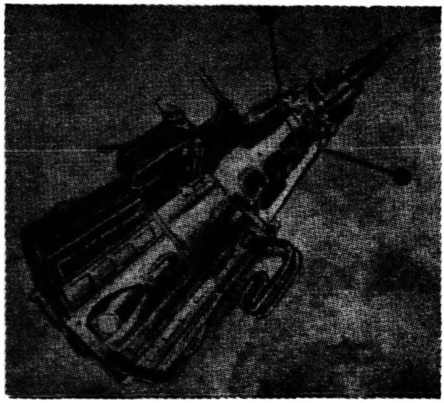
Investigation of outer space with the help of artificial satellites was carried out according to a special composite program announced by Tass on March 16, 1962.

The number of satellites launched in the "Cosmos" series exceeded 400.

Perfection of rocket-space technology made possible not only wider

and deeper development of space research but also the placing of earth's artificial satellites at the service of the national economy. Application of special-purpose satellites for communications, meteorology, navigation, study of natural resources and oceans has much scope.

Along with the flights of spacecraft in near space, the Soviet cosmic (research) program has an important place for study of the moon and planets of the solar system as well as interplanetary space. This study is carried out with the help of automatic interplanetary stations. The program has a definite place for manned flights. At this stage, however, the leading role in the investigation of planets and our satellite moon is given to unmanned spacecraft. They are substantially cheaper than manned ones and are capable of transmitting or delivering to earth valuable scientific information from such regions of outer space as cannot be visited by man for the time being.



One of the first artificial satellites of the earth.

Flights of automatic interplanetary stations began on January 2, 1959, with the launching of a cosmic rocket toward the moon. For its exit from the earth's gravitational field the rocket was given escape velocity.

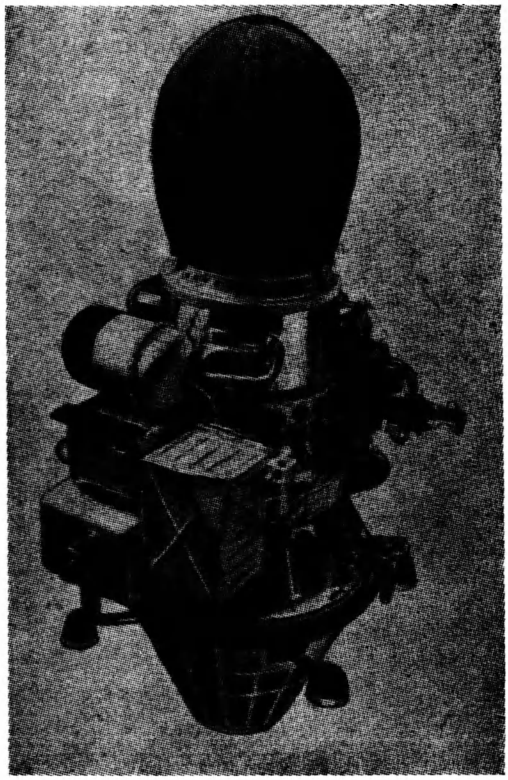
Use of the spacecraft opened up the greatest possibilities for study of the moon. The scientific and technical tasks to be undertaken by the automatic stations during their flights to the moon are worked out taking into account the information already available. This gets progressively more complicated with each launching.

Automatic interplanetary stations (AMS) in the "Luna" and "Zond" series carried out a large volume of investigations of the moon, lunar space and interplanetary space, took photographs of both the visible and the opposite sides of the moon from various distances and also photographed the earth from the outer space. The "Zond" stations made it possible to work out a return procedure to the earth for spacecraft approaching at escape velocity and to test the outfit and other systems of interplanetary spacecraft.

The flight of station "Luna-16" marked an outstanding achievement of Soviet science and engineering. On September 20, 1970, this station made a soft landing on the lunar surface. After having collected samples of lunar soil with the help of a drill the rocket with the return package took off

from the moon. The return package landed on the earth on September 24, 1970.

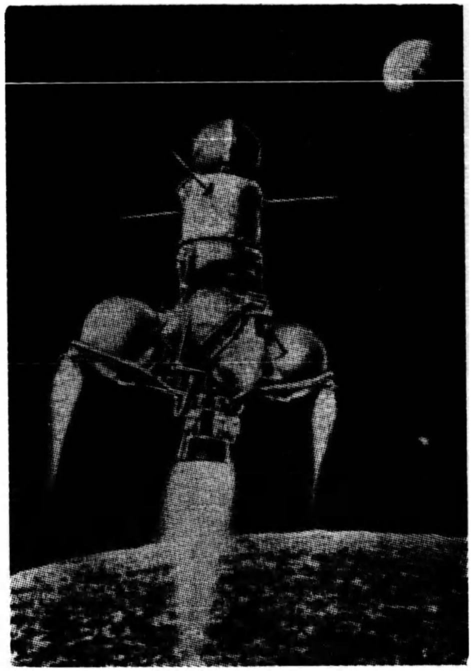
The station "Luna-16" carried out a new task: automatic delivery of lunar soil to the earth.



A Soviet automatic station "Luna-9," which made a soft landing on moon.

In accordance with the Soviet cosmic research program, a unique experiment in constructing and utilizing the lunar transport system was accomplished in our country. On November 17, 1970, the automatic station "Luna-17" landed on the moon to deliver in the region of the Sea of Rains the self-propelled device "Lunakhod-1."

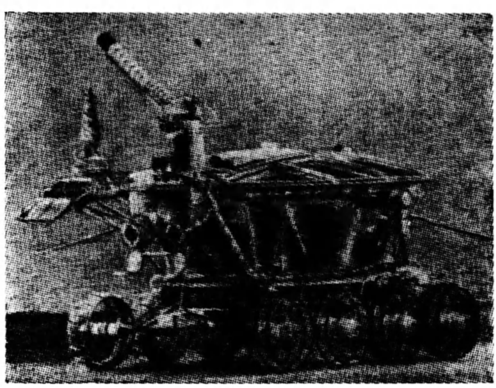
Movement of the first "Lunakhod" on the lunar surface signals the approach of a new stage in the investigation of the universe. In the near future one can foresee the appearance of mobile, automatic equipment which will be able, with the help of a manipulator, to pick out samples of lunar soil and deliver them to the rocket destined to return to earth. Operators on the earth will be able to control these manipulators. Automobiles to transport astronauts to different regions of our cosmic neighbor



Soviet automatic station "Luna-16," which delivered samples of lunar soil to the earth.

will also make their appearance, with corresponding benefit to research.

The flight of "Venera-4"* on the eve of the 50th anniversary of the Great October Revolution was an outstanding victory for Soviet science



Self-propelled device "Lunakhod-1."

*Venus-4.

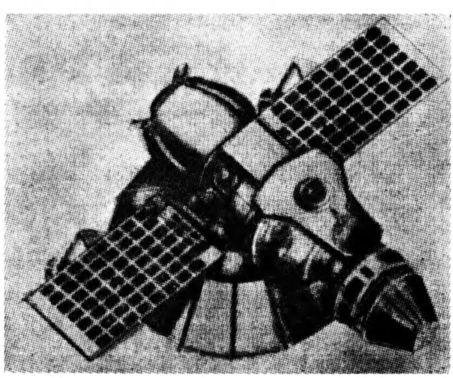
and engineering. On October 18, 1967, for the first time in the history of interplanetary space research, the automatic station reached Venus, performed a smooth descent into its atmosphere and transmitted to earth the results of measurements of the fundamental parameters of the atmosphere. Unique scientific data were obtained as a result of investigations carried out right in the atmosphere of Venus.

On May 16 and 17, 1969, a still more complicated cosmic experiment was carried out. First the station "Venera–5" and subsequently the station "Venera–6" reached the planet. Their re-entry devices performed a smooth descent in its atmosphere. They carried out a wide range of complex measurements and transmitted valuable information to earth. The stations carried to the surface of Venus a pendant bearing a bas-relief of Vladimir Il'yich Lenin and the State emblem of the Union of Soviet Socialist Republics.

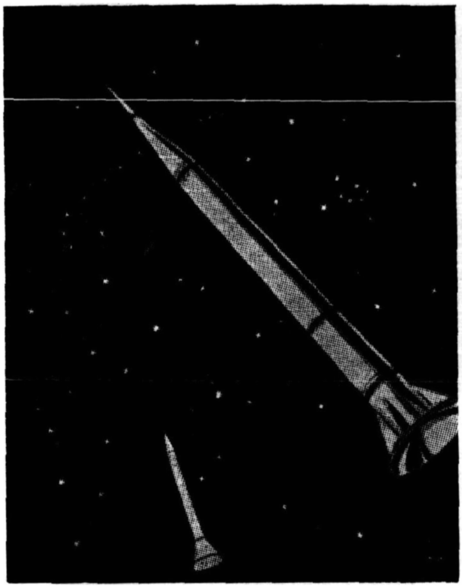
As a result of the flights of "Venera–4," "Venera–5" and "Venera–6" the chemical composition of the atmosphere and the temperature and density at different altitudes above the planet's surface were determined. The stations "Venera–5" and "Venera–6" concluded measurements while at a distance of about 20 km from the planet's surface. During the flight of "Venera–7" direct measurement of the parameters of the atmosphere of Venus was continued right down to the planet's surface.

It was the first time that scientific information had been transmitted directly from the surface of any other planet of the solar system. The scientific results achieved by "Venera–7" have considerably widened our knowledge of the planet nearest to the earth. A successful and important step has been taken in the study of outer space and the planets of the solar system.

The main orientation of Soviet (cosmic) research is manned flights in the cosmos.



Automatic Interplanetary Station "Venera–7."



Toward mysterious worlds.

April 12, 1961, will go down in the history of mankind as the beginning of man's ingenious penetration into the cosmos. On the morning of this day, the spaceship *Vostok** was launched from the cosmodrome Baikonur. This spaceship was manned by the Soviet pilot-astronaut Yurii Alekseevich Gagarin, who opened the era of human flight into the cosmos.

Since then many outstanding flights aboard the spaceships *Vostok, Voskhod*† and *Soyuz*‡ have been made by heroic Soviet astronauts.

The development of systems on the new Soviet spaceship *Soyuz* and the completion of a number of complicated experiments during flight in the past year are important steps toward the creation of orbital stations.

Man has already visited the moon. Before him lies a great deal of the new and unknown.

The black abyss of the cosmos. Unwinking bright stars. A gigantic interstellar liner moves through a huge, inconceivable galactic emptiness toward a distant, unknown planet. Aboard are the courageous cosmonauts who have conquered the infinite universe in man's most glorious hour.

*East.
†Rise.
‡Union.

SECTION TWO

Aircraft

PHYSICAL PRINCIPLES OF FLIGHT

Composition and structure of the atmosphere

The atmosphere is the air that envelopes the earth. It is a physical mixture of oxygen—21%, nitrogen—78% and other gases (argon, hydrogen, carbon dioxide, helium)—1% (percentages are by volume). It covers the earth in a very thin layer in comparison with the radius of the earth. The air up to an altitude of 5.5 km contains nearly 50% of the mass of the whole atmosphere, up to 10 km 75% and up to 20 km nearly 94%, i.e. almost the whole of the mass of the atmosphere. The composition of the atmosphere remains almost unchanged up to very great altitudes.

The atmosphere is subdivided into the lower portion, up to 40–50 km, and the upper portion, extending to great distances from the earth (Fig. 1).

The lower atmosphere in its turn is divided into two parts: The troposphere, a layer of air varying in thickness from 8 km at the poles to 16 km at the equator; and the stratosphere, the layer of air from 10 to 50 km above the surface of the earth. In the troposphere water vapor is condensed, clouds are formed and the displacement of air masses takes place in vertical (thermal streams) and horizontal planes. The weather is formed here.

The stratosphere is the layer of atmosphere with a practically constant temperature of $-56.5°C$.

The upper atmosphere is subdivided into a number of layers: mezosphere (50–80 km), ionosphere (80–500 km) and the layer extending from 500 km to the edge of the atmosphere, the exosphere.

The upper atmosphere is characterized by low pressures and density, intensive processes of dissociation (disintegration of molecules) and ionization (formation of plasma from ions and electrons) of air particles.

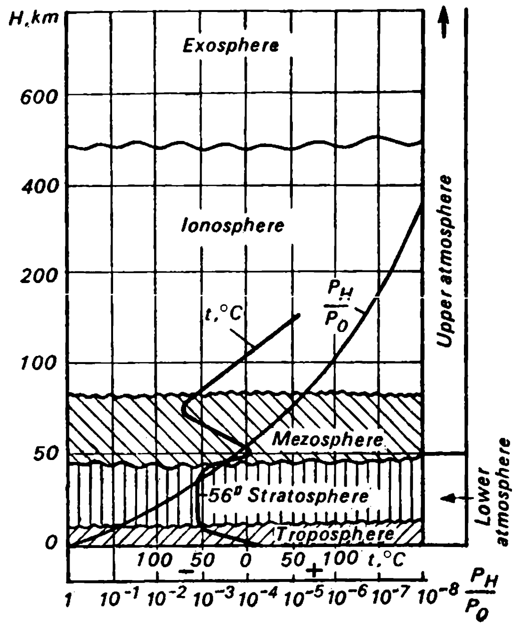


Fig. 1. Structure of atmosphere:

t °C—temperature in degrees Centigrade; p_H—pressure at height; p_0—pressure at sea level; H—height.

Variation in the density, pressure and temperature of the air with altitude

Density and pressure of the atmosphere generally decrease with altitude. Due to turbulence in the troposphere this decrease is not uniform but varies within certain limits depending on the season and the latitude of the place. This gives rise to difficulties and inconvenience in calculating the flight characteristics of aircraft which to a great extent depend on the density and (at high flight speeds) the temperature of the air during flight.

The considerable changeability of the state of the atmosphere makes it necessary to use yearly average characteristics. For the sake of practical calculations a conventional atmosphere—the International Standard Atmosphere (ISA)—based on the statistical data of many years was adopted.

At an altitude of 10 km the pressure of air is less than that at sea level by 3.8 times. Its density is one-third. At 25 km the pressure is only 2.4% and density of the air only 3% of their values at sea level. At a height of 220 km both pressure and density are a few billionths of those values.

Air temperature in the troposphere falls rapidly with increasing altitude. In the stratosphere it remains almost constant. In the mezosphere it begins to rise at a rapid rate and attains a maximum of +8°C. This is because the sun's ultraviolet rays are absorbed by the ozone present there. At heights

of 60–80 km air temperature again falls to between −70° and −75°C.

The mezosphere is of utmost importance for life on earth because the sun's severe ultraviolet radiation, which is destructive of living creatures and plants, is absorbed by it.

The rise in air temperature in the ionosphere is explained by the intense dissociation and ionization and intensive absorption of solar radiation. The ionosphere extends up to altitudes of 300–500 km and has several layers. The presence in the upper regions of the atmosphere of ionized layers containing free electrons and negative ions creates the conditions for the reflection of radio waves. Above the ionosphere there is the exosphere. It consists of both charged and neutral atoms, mainly atoms of hydrogen.

The exosphere, like the ionosphere, is an electro-conducting medium moving in the earth's magnetic field. Owing to this strong electric currents are induced in the upper atmosphere, promoting additional warming of the atmosphere.

Thus the atmosphere is a non-homogeneous medium where there are constant complicated physical, electro-magnetic and photochemical interactions which are of the utmost importance for all processes on earth.

Principle of aircraft flight

An airplane is heavier than air. So for horizontal flight to be possible there must exist a force capable of balancing its weight. This force appears during the movement of the aircraft.

An aircraft moving under the action of thrust developed by the engine displaces a certain volume of surrounding air with its wings which are set at a small angle to the direction of the aircraft's motion. They push the air downward and forward.

In accordance with Newton's third law of motion—"Action is equal to reaction"—the air that is being pushed aside gives rise to a force equal in magnitude but opposite in direction.

Displacement of air by the moving aircraft results in variation of air pressure around the aircraft. The sum of the elementary forces of pressure acting on the surface of the aircraft is the resultant of aerodynamic forces. It is directed upward and backward.

Projection of the sum of elementary forces of pressure on the plane perpendicular to the direction of motion is the lift, while projection of these forces in the direction of motion is the drag.

The weight of the aircraft and lift constitute the first pair of basic opposed forces during flight (Fig. 2).

In order to move through the air an aircraft must have a propulsive force—the thrust, necessary to overcome the aircraft's inertia and the air resistance (drag). This is the second pair of opposed forces in flight: thrust and drag.

If the forces in these two pairs and their moments with respect to the center of mass of the aircraft are equal among themselves, i.e. weight is equal to lift and thrust is equal to drag, then the aircraft moves uniformly in a straight line. If forces in a certain pair are not equal, then a change in motion takes place either in a vertical (ascent, descent) or in a horizontal plane (acceleration, deceleration). Unequal moments make the aircraft turn in the respective plane.

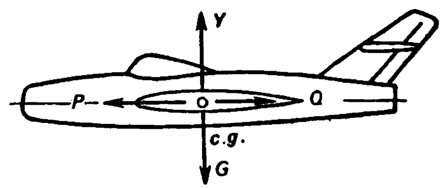


Fig. 2. Equilibrium of forces in steady horizontal flight of aircraft:

Y—lift; G—weight of aircraft; P—thrust of the engine; Q—drag.

The gross weight of the aircraft is the sum of the weights of the payload, engines, fuel and different components of the aircraft structure. Designers strive to make the payload of an aircraft as large as possible and keep the structural and airborne weight of the aircraft to a minimum.

Aerodynamic forces and their nature

As mentioned above, the lift and the drag are natural reactions of the air displaced by the moving aircraft.

The aircraft as it were "pushes away" the air in front and "leans against" it during movement. Due to this the distribution of pressure in the volume of air around the aircraft is changed. There appear zones of increased and decreased pressure. We will consider in detail what happens in this case.

Lift. The magnitude of air pressure depends on the velocity of the aircraft, the size of its parts, their shape and location with respect to the flow of air.

In aerodynamics, while examining such situations, the law of reversibility of motion is usually applied for convenience. It is assumed that the air, not the aircraft moves, that it "flows past" the aircraft, is decelerated or accelerated when it meets the aircraft parts and is deflected or "beveled."

We will also adopt this convention. Let the air flow around the wing of an aircraft placed at a small positive angle a (Fig. 5) to the direction of flow. The stream of air is decelerated in front of the wing and then is divided into two parts. One part flows over the upper surface of the wing while the other flows under the lower surface. Behind the wing the two flows join up again.

Since the wing has a bulging shape the upper stream of air moves a greater distance than the lower one. Due to this the velocity of the upper stream increases and its pressure decreases. The velocity of the lower streams is decreased and the pressure is increased (Fig. 3).

The direction and magnitude of the change in stream velocity are determined by the distribution of pressure around the wing and depend on the "airfoil," i.e. shape of the wing section and the angle between the chord of the wing section and the direction of flow, called the angle of attack.

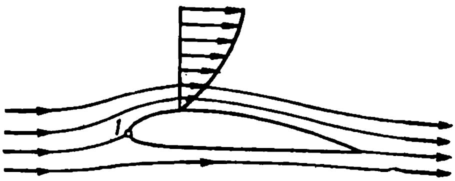


Fig. 3. Local velocity of air around the body: *1—dead center.*

The sum of the projections of elementary pressure forces (rarefaction) acting on the surface of the airfoil, taken on a plane perpendicular to the direction of flow, is the lift, while the sum of projections of these elementary forces taken on a plane parallel to the direction of airflow is the drag.

A wing with a symmetrical airfoil has lift only if its angle of attack is other than zero. At zero angle of attack lift does not occur since the flow around the wing is symmetrical. On increasing (decreasing) the angle of attack of the wing the symmetry of the flow is destroyed. The wing as it were twists the flow and bevels it. The difference in pressures on the upper and lower surfaces of the wing creates the lift. The more the flow is beveled, i.e. the more the air is accelerated on one side and decelerated on the other, the greater the lift.

Drag. The drag of an aircraft is made up of profile drag, frictional drag and induced drag.

Profile drag: The magnitude of pressure acting on a body in a plane parallel to the direction of airflow depends on the difference in pressures on the leading and trailing parts of the body and its shape.

This force, measured when a body is so placed in the airflow that no lift is created, is called profile drag or form drag. To reduce this drag the aerodynamic body is given a shape that eliminates the large difference of pressure at its leading and trailing parts.

Frictional drag: Close to the surface of the wing and any other part of the aircraft in the airstream the particles of air are retarded as if they were sticking to it. Only at a certain distance from the surface do the air particles acquire the free stream velocity. This layer of air is called the boundary layer. Its thickness depends on the degree of smoothness of the surface and the viscosity of the air.

Energy lost in the boundary layer is equal to the work done by the frictional force of air. The corresponding force is named the frictional drag and depends on the total surface of the aircraft parts exposed to the airstream.

In the boundary layer the pressure is more than that in the free stream. In certain regimes of flow a moment can come when a part of the boundary

layer, striving to "pour" into a zone of lower pressure, comes off the wing surface and gets twisted. During this process vortices are formed and there is loss of energy. Vortices are formed not only due to friction but also as a result of the imperfect shape of a wing, when its protrusions or steeply varying cross section give rise to a large pressure loss in neighboring regions.

Induced drag: Arises from the necessity of spending energy to divert the flow of the airstream downward in order to create the lift.

If the wing has lift acting upward in horizontal flight then there exists a force acting on the airstream in the opposite direction, deflecting the air downward.

The higher the lift of the wing the greater the deflection of the airstream and the greater the induced drag.

One must remember that the free airstream is essentially slowed down when drag is present and deflects downward when there is lift.

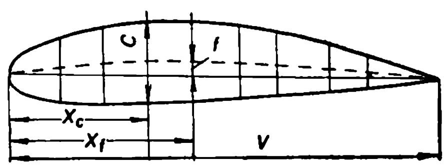


Fig. 4. Geometric parameters of wing profile: *c—maximum thickness, f—maximum bend of the central line, b—chord of the profile, x_c—distance between the maximum thickness of the profile and its nose, x_f—distance between the maximum bend angle and the nose of the profile.*

Aerodynamic coefficients. The shapes of wing profiles vary widely. Their most characteristic peculiarities are maximum camber f (Fig. 4) measured as percentage of chord length b, the distance x_f of its location along the chord and the maximum thickness c, also measured as a percentage of chord length.

It has been experimentally established that the magnitude of lift (Y) is equal to half of the product of the density ρ of air, the square of the airstream velocity V^2, the area of the wing S and the coefficient of lift c_y:

$$Y = c_y\, S \frac{\rho V^2}{2} = c_y\, Sq,$$

where q is the velocity head (dynamic pressure).

Coefficient c_y is derived from experimental data and depends on the position of the wing profile with reference to the airstream, i.e. on the angle of attack. The magnitude of c_y is equal to the lift measured at a given angle of attack divided by the area of the wing and velocity head.

Similarly, if the magnitude of the measured drag force is divided by the product of the wing area and velocity head, we get the coefficient of drag c_x.

The introduction of coefficients c_x and c_y made it possible to compare wings of various design parameters, fuselages, etc. For determination of

these coefficients tests are usually carried out in wind tunnels which are devices for creating a flow of air of the required velocity.

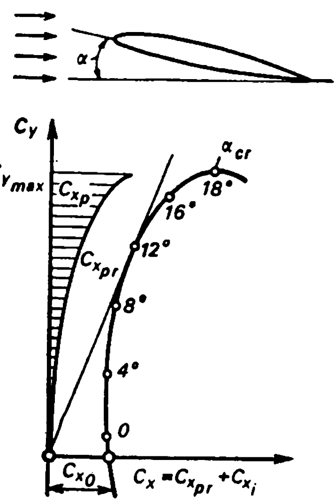


Fig. 5. Lilienthal polar:

c_y—coefficient of lift; c_x—coefficient of drag; c_{x_i}—coefficient of induced drag; $c_{x_{pr}}$—coefficient of profile drag; a—angle of attack of wing (section) profile; a_{cr}—critical angle of attack at which flow separation begins and c_y—falls; c_{x0}—coefficient of drag at zero lift.

A model of the aircraft, or part of it, is mounted in the tunnel on special suspension connected to an aerodynamic balance with the help of which the lift and drag are measured. Coefficients of lift c_y and drag c_x are obtained from the dimensions of the model and magnitude of velocity head.

By passing a current of air over the wing at different angles of attack the coefficients c_y and c_x are calculated by plotting the results of the experiment on graphs.

Characteristics of profile and wing. To calculate the flight characteristics of aircraft it is necessary to know the magnitudes of coefficients c_y and c_x at every angle of attack. Profile characteristics are plotted graphically. The curve thus obtained is called a Lilienthal polar or simply polar. It shows the relation between c_y and c_x at different angles of attack (Fig. 5).

The purpose of the wing is to create lift. The appearance of drag simultaneously with lift is undesirable but it is unavoidable. One of the main characteristics for a wing is the lift-to-drag ratio expressed by the formula $K = \frac{c_y}{c_x}$. This ratio shows how many times the lift exceeds the drag at a given angle of attack. Obviously the larger the lift-to-drag ratio, the better the wing fulfills its purpose.

CONSTRUCTION OF AIRCRAFT

Every aircraft is built for a definite assignment with the concrete aim of carrying out clearly defined tasks. This is the basis of the differences in the requirements of flight characteristics of aircraft, their load lifting capacity arrangements for accommodating the crew and the passengers and the "performance" of the aircraft. These differences, naturally, have an effect on the construction of aircraft and their aerodynamic configurations (Fig. 6).

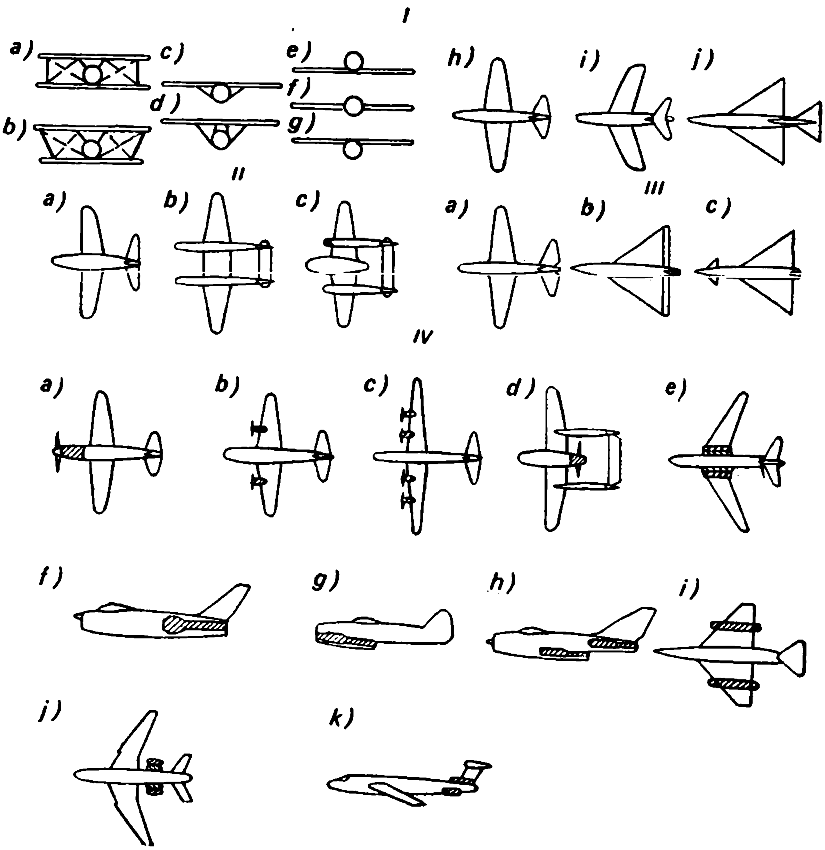


Fig. 6. The most commonly used types of aircraft:

I. Shape and location of wing: *a—single-strut wire-braced biplane; b—wire-braced sesquiplane; c—strut-braced monoplane; d—strut-braced monoplane parasol; e—cantilever monoplane with low-set wing; f—same with mid-wing; g—same with high-set wing; h—monoplane with straight tapered wing; i—monoplane with swept wing; j—monoplane with delta wing.* II. Type of fuselege: *a—single-fuselage type; b—twin-fuselage type; c—gondola.* III. Location of fin assembly: *a—aircraft with common tail unit; b—tailless aircraft; c—aircraft with horizontal nose plane.* IV. Location of power plants (engine): *a—single-engine aircraft with engine in the front; b—twin-engine aircraft; c—four-engine aircraft with engines mounted on the wing; d—single-engine aircraft with pusher propeller; e—twin- or four-engine aircraft with engines mounted on the wing root; f—single engine aircraft with engine in the tail part of the fuselage; g—single-engine aircraft with engine in the nose of the fuselage; h—twin-engine aircraft with engine mounted in the fuselage; i—twin-engine aircraft with engines mounted on the wing or under it; j—four-engine aircraft with engines mounted on the pylons of the rear part of the fuselage; k—three engine aircraft with two engines mounted on the pylons of the rear part of the fuselage and one in the tail fin.*

Any aircraft, irrespective of its purpose, has the following basic parts: wing creating lift, power plant creating thrust, fuselage comprising compartment for the crew, passengers, freight (and often fuel and power plant), tail unit in the form of fixed and movable planes used for stabilizing aircraft or changing its position in the air, chassis (landing gear) and control systems (Fig. 7).

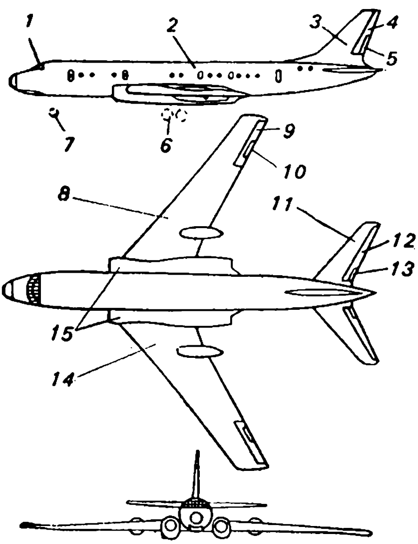


Fig. 7. Scheme of aircraft:

1—cockpit canopy; 2—fuselage; 3—tail fin; 4—rudder; 5—rudder trimmer; 6—main wheels; 7—nose wheel; 8—right wing; 9—aileron; 10—aileron trimmer; 11—stabilizer; 12—elevator; 13—elevator trimmer; 14—left wing; 15—engines.

Wing

The wing creates lift due to the difference in pressure on its upper and lower surfaces. The pressure forces are distributed unevenly around the wing profile and act directly on its surface. Their magnitude varies according to the velocity head and angle of attack. For every angle of attack there is a corresponding distribution and magnitude of pressure forces and, consequently, lift-to-drag ratio.

In acting on the wing covering the airstream tries to bend the wing in horizontal and vertical planes and twist it.

Besides the pressure forces exerted by the air, i.e. air load, on the wing so-called mass forces are set in motion due to the weight of the wing's structural elements as well as the aggregates and loads accommodated in it and the inertia forces which are proportional to the mass of these elements. Moreover, at the points where the wing is joined with other parts of the aircraft reaction forces due to the wing's interaction with these parts appear.

The wing is so designed that at minimum weight it would withstand all the load acting on it during flight and maintain the necessary aerodynamic configuration that depends on the required flight data.

A wing consists of longitudinal elements: spars and stringers, and transverse elements: ribs and coverings (Fig. 8).

A spar is something like a girder with upper and lower flanges connected together with webs or struts. It transmits to the wing joints vertical, also called shear forces and takes up the bending moment of these forces which is transmitted to its flanges. Wings are either single, double or multi-spar.

Stringers are longitudinal elements fixed to the upper and lower wing coverings in order to give them stiffness and to take up together with the spar flanges the bending moment due to vertical forces.

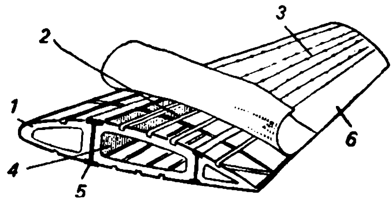


Fig. 8. Basic elements of wing:
1—rib; 2—stringer; 3—covering; 4—spar web; 5—spars; 6—aileron.

Ribs are the basic elements forming the aerodynamic configuration of the wing section. The wing covering is fixed to them both directly and through stringers. They take up the air load and transmit it to the spars.

Taken together, the elements of the wing form a thin-walled closed structure which consists of a frame and a covering functioning jointly.

The torque, appearing due to the fact that the resultant of all the forces does not pass through the shear center[1] of the wing section, is taken up by the wing covering and is transmitted through the last rib to the wing joint or directly to the fuselage sheathing if the wing is joined to it along the profile. The higher the aircraft's flight velocity, the greater the velocity head and, consequently, the load on the aircraft elements. In order to provide the required strength and rigidity for fast aircraft it becomes necessary to thicken the covering of the wing, tail plane and fuselage and to strengthen other structural elements.

With the reduction of relative thickness of the wing (ratio of maximum thickness of wing to its chord) and increase of load on it the wing covering began to play a very big role in the design. Besides the direct air loading and torque it takes up a considerable part of longitudinal stresses due to bending moment.

It is known that the rods and other structural elements having a large length-to-thickness ratio lose their stability (bulge, bend) under longitudinal compression well before the load reaches a crippling value due to compression.

To prevent the wing covering from losing stability at the gap between the ribs it is reinforced by longitudinal elements—stringers. With the same purpose honeycomb and other constructions are used.

On the wing there are ailerons, which are devices for lateral control of the aircraft, and high-lift devices: slats, guided leading edges, split and plain flaps and devices for blowing or sucking the boundary layer.

The wing is the most important part of any aircraft. This is so not only because of its function but also because it accounts for 12-16% of the weight of the aircraft and up to 50% of the total resistance.

[1]Shear center is a point on the cross section of a structure such that if a lateral force passes through it no torque arises and no torsion accompanies the bending.

The wings of different types of aircraft differ from each other in plan (when seen from above), their location with respect to the fuselage, dihedral (front view), profile and specific loading (i.e. loading per square meter of the surface), constructional details and material.

High-lift devices

High-lift devices increase the lift and simultaneously the drag of the aircraft. The increase of lift is required during take-off in order to reduce the required take-off velocity of the aircraft and the length of the take-off run and during landing to decrease the approach speed and thus, as a result of increased resistance, to reduce the landing run.

It is possible to increase the lift of the wing at constant velocity by employing several methods. For example, by increasing the area of the wing or its angle of attack or by changing the wing camber so as to increase the value of coefficient c_y at the same angle of attack.

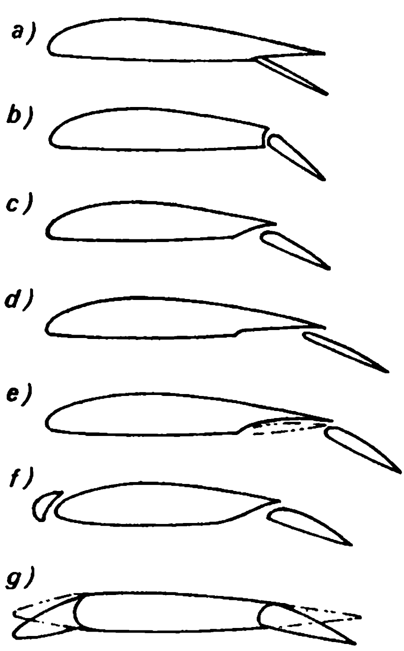


Fig. 9. Various types of high-lift devices: *a—split flap; b—plain flap; c—slotted flap; d—zap flap; e—fowler flap; f—slat and flap; g—guided leading edge and flap.*

The first method, due to constructional complexity, is very rarely used in practice. The second method, i.e. increasing the critical angle of attack, which can be done with the help of slats, has little effect. The third method, increasing the camber (concavity) of the wing section (Fig. 9), is achieved by deflecting either the leading edge of the wing or its trailing edge (flap) or special flaps located on the lower surface of the wing, or by employing a combination of the above-mentioned methods. This increases the difference between the pressure forces on the upper and lower surfaces of the wing as a result of which c_y is increased at the same angle of attack.

It is also possible to increase the lift by blowing or sucking the boundary layer from the upper surface of the wing or jet flaps. The use of these methods, however, requires a large amount of energy.

The high-lift devices are so designed as to offer minimum possible drag while in the non-working position and to impart, while functioning, no

variations in aircraft performance that the pilot would find hard to control.

Let us look at the operation of these devices one by one!

Deflection of the leading edge of the wing: At large angles of attack hinders the separation of the flow, making it possible to reach large angles of attack and consequently, high c_y. The increased profile camber (convexity) thus obtained leads to an additional increase of c_y. Since for profiles with a sharp leading edge, used for the wings of fast aircraft, flow separation begins even at small angles of attack, such wings in most cases are designed with a deflecting leading edge.

Slats (leading edge): Are small profiled surfaces located, as their name implies, on the leading edge of the wing. When the slat is pressed to the wing it forms part of the wing profile but when it moves away from the wing a profiled slot is formed between the slat and the wing. The air flowing through this slot moves along the upper surface of the wing, blowing the boundary layer. As a result the flow separation is delayed up to larger angles of attack and c_y increases.

Slats are usually used only to improve the lateral stability of aircraft during flight at large angles of attack. They are fixed with respect to the wing (with a fixed slot) and movable (can be pressed against the wing during flight with small angles of attack).

Movable flaps are operated either manually with the help of the mechanism provided or automatically in response to the suction force acting on the flap at large angles of attack.

A trailing edge flap on a wing makes it possible to increase c_y without increasing the angle of attack.

The simplest device is the split flap, which is part of the lower surface of the wing occupying 25–30% of the chord and up to 60% of the aircraft wing span. It can be deflected up to 55–60°.

More complicated than split flaps are zap flaps which are deflected downward and at the same time move backward along the chord, increasing the effective area of wing.

At a fairly late stage plain and fowler flaps began to be used. A plain flap is the rear part of the wing profile that can deviate downward through a certain angle. Flaps can be either single or double. If the rear part of the profile not only deviates downward but also moves backward it is a fowler flap.

A narrow stream of air flowing through the wing and flaps blows the boundary layer from the upper surface of the flaps, thus securing an unseparated flow over them and, consequently, providing an opportunity to obtain large c_y.

Since the increased wing resistance is useful during the aircraft's landing run and dangerous during the take-off run the angle of deviation for high-

lift devices during take-off is kept smaller than that during landing.

Increase of the lift of a wing is also possible by increasing the intensity and regulating the airstream flowing over it. But in this case it is necessary to spend a certain amount of energy.

Theoretically the most effective devices are blowing or sucking the boundary layer from the upper surface of the wing. Suction increases the velocity of flow and consequently the vacuum above the wing surface in the region in front of the point of suction. Blowing does the same practically over the whole chord of the wing. In blowing or sucking the boundary layer, with the increase in c_y there takes place a simultaneous decrease in the wing drag and consequently the lift-to-drag ratio is increased. The faster the air is blown the larger the increase in c_y.

The jet flap is another means of increasing lift. In this method either air or gas is forced through a slot in the trailing edge of the wing at a certain angle with the chord. A jet from the slot plays the part of an original flap. A stream of air as it were flows around a fictitious wing of a larger chord and camber than those of the actual wing. The distribution of pressure over the actual wing and its supporting capacity, mainly in the region of the trailing edge, increase. The jet flap has not been widely used due to the weight of the gas feeding system and other operational complications.

Fuselage

The fuselage unites many parts of an aircraft: wing, tail plane, undercarriage and power plant. In it are accommodated the crew, passengers, equipment, freight and in some cases fuel, ammunition and engines (Fig. 10).

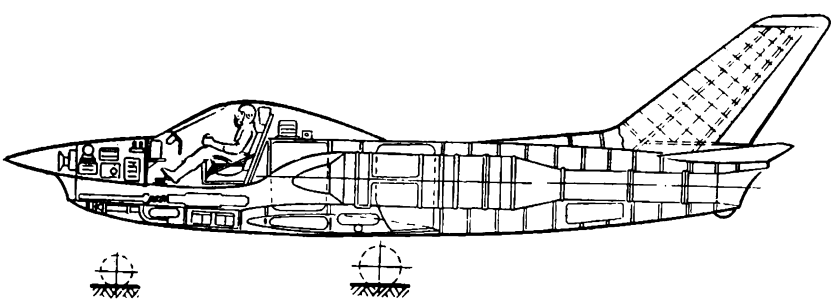


Fig. 10. Fuselage arrangement of a fighter aircraft.

There are considerable forces acting on a fuselage due to the aircraft parts joined to it, due to the weight of freight located in it, due to its own weight and also due to aerodynamic surface forces (pressure and vacuum).

The magnitude of the latter forces at different places (canopy, nose) can be as high as 7,000 kg/m^2.

In addition, pressurized fuselage are loaded from the inside due to the excess pressure inside which is more than the air pressure outside.

The fuselage of a modern aircraft is a frame with a thin-walled covering. The frame is built from a group of longitudinal elements (longerons and stringers) and lateral ones (formers). Stringers and longerons are loaded with axial stresses (tensile and compressive) against bending moments of the fuselage. Stringers serve also as a reinforcement to the covering and increase its critical stresses (stresses at which it yields). Formers preserve the shape of the fuselage cross section. They serve as supports for stringers and coverings and take up the local aerodynamic loading. Reinforced formers transmit local concentrated forces to the covering.

The covering gives the fuselage a streamlined shape. It is subjected to normal (compressive and tensile) and tangential (shear) stresses arising during bending and twisting of the fuselage.

The fuselage usually has many big openings for access to equipment and freight, bomb bays, cabins, armaments, doors, under carriage, etc.

The nose of the fuselage of a supersonic aircraft is made sharp so that oblique shocks are formed and there is reduction in wave drag (these will be described later).

Livable conditions for passengers and crew at high altitudes of flight are secured by using pressurized cabins. A higher pressure of air with concentrated oxygen, as compared with the atmospheric pressure at the given altitude of flight, is built into these cabins. Normal temperature is maintained by thermal insulation and by heating and cooling equipment.

The most important parts of a pressurized cabin are the windows and the canopy. During flight through air at low temperatures the glass of cabin windows can become fogged or be covered with ice, obstructing visibility. Therefore either electrical or air heating of windows is installed or the windows are made of two panes of glass with an air gap between that is dried with the help of special cartridges. The proper tightness of riveted joints is achieved by using multibanked seams of specially treated strips.

Undercarriage

The undercarriage permits an aircraft to park and move along the ground while taking off, landing and taxing. On modern aircraft the undercarriage can be retracted during flight.

The most widely used are the two types of tri-supported undercarriages. In the first type (Fig. 11a) the main supports are located in front of the center of gravity and in the rear there is a tail wheel. In the second type (Fig. 11b) the main supports are behind the center of gravity and in the front there is a nose wheel.

In practice the undercarriage with the nose wheel is more widely used. The main reason for this is that the "tricycle undercarriage" (as the undercarriage with a nose wheel is called) provides stability to the aircraft during take-off and landing runs and prevents it from nose tilting, i.e. "nosing-over."

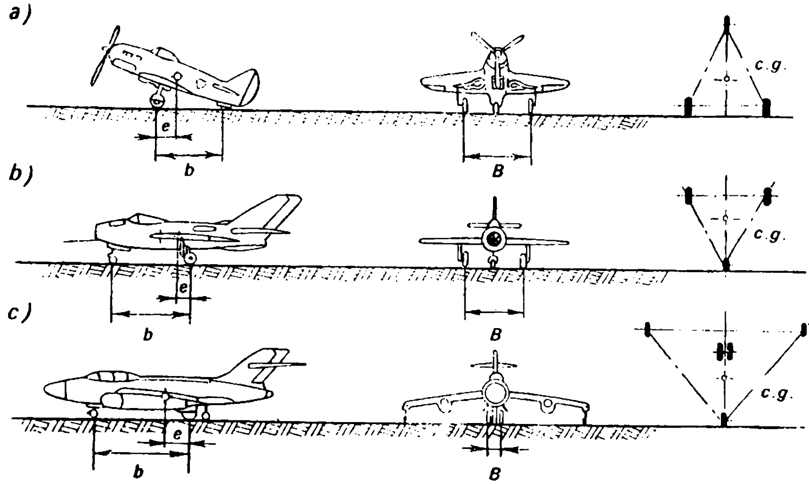


Fig. 11. Schematic diagrams of aircraft undercarriages:
e—stagger of main wheel; b—wheel base; B—(undercarriage) track.

The main supports of the undercarriage take up to 85% of the aircraft's weight. The tail or nose support carries nearly 15% of the weight. To facilitate movement of the aircraft on the ground it is made steerable by foot pedals. The main wheels retract into either the fuselage or the wing. For retraction a suitable space is left clear, its size depending on the number of wheels, their breadth and diameter.

The smaller the pressure in the tyres of the wheels the lower the unit pressure on the ground. The wheels then "stick" to the ground less, enabling the aircraft to take off and land on dirt landing strips. For such runways, however, the size of the wheels is increased.

Low pressure in the tyres is an asset in rainy weather when the ground is soaked. Good "trafficability," (utilization factor) is the top priority for aircraft used in agricultural and ambulance aviation, passenger aircraft of local airlines and military aircraft in front-line combat.

Modern fast aircraft have thin wings and densely filled fuselages. In their case retraction of the wheels has become a difficult problem to solve. So they are fitted with wheels with high-pressure tyres and are obliged to operate from concrete runways.

When there are two or more wheels on each of the main supports they

are mounted on special trolleys that ensure uniform load on the wheels during a change in the aircraft dip angle and deceleration.

The location of the undercarriage and the height from the ground of the aircraft's center of gravity have a very important role in the design of aircraft. In the case of a "tricycle undercarriage" the main wheels are situated at such a distance behind the center of gravity that its projection at take-off and landing angles of attack (plus a safety margin of 2–3°) do not fall outside the line joining the right and left supports. This prevents the aircraft from nosing over and provides stability during the landing run.

The location of the main supports along the wing, i.e. track width, depends on the arrangement of wheel retraction. The distance between the supports is determined taking into account the combined effect of track width and undercarriage height on aircraft stability against sideslip while landing in a cross-wind.

Aircraft with small track width, particularly with a twin-support, so-called "bicycle" undercarriage (Fig. 11c), are provided with additional retractable wheels at the wing tips.

The height of the undercarriage is kept to the minimum possible for economy in weight and simplicity in retraction.

Retraction and release of the undercarriage are carried out by systems which operate automatically when the pilot switches them on. These are either hydraulic, pneumatic or electro-mechanical. The systems are usually duplicated as primary and emergency systems.

The undercarriage legs have shock-absorbers to dissipate shocks during the aircraft's movement on the ground and to damp vibrations. Nowadays oil-air (Oleo-aerol, Oleo-pneumatic*) shock absorbers are used exclusively in practice.

Aircraft control

By aircraft controls are meant the devices and systems designed to turn control members (e.g. the rudder) in order to change the aircraft's position in the air, namely aircraft pitching, i.e. the inclination of the longitudinal axis to horizontal, rolling and turning.†

Aircraft controls include: control column for elevator and ailerons, control pedals for rudder, control levers for various accessories and aircraft systems, including control of power plants and the fuel system, and system of cables, rods, rockers, ropes and hand levers.

Control is divided into hard control, in which the operating levers and aircraft control members are connected with the help of rods (pipes) with hinged ends of adjustable length, soft (rope) control and mixed control.

*Ref. *From the Ground Up* by Sandy A.F. McDonald—Translator.

†Sometimes the term "Yawing" is used—Translator.

In order to change the position of the aircraft in the air it is necessary to turn it in a certain plane with respect to the center of gravity. For this a controlling force situated at a certain distance from the center of gravity is necessary. This is created by turning the aircraft control members.

Turning of the elevator or the whole stabilizer changes pitching, that of the ailerons changes rolling. Turning of the rudder changes the yaw angle, i.e. the angle between the plane of aircraft symmetry and the direction of its motion.

A forward movement of the control column (wheel) deviates the elevator downward, as a result of which a controlling force directed upward appears on the horizontal tail plane and gives rise to a diving moment (aircraft's nose goes down). Deviation of the control stick (wheel) toward the pilot gives rise to a pitching-up moment (aircraft's nose goes up).

A movement of the control stick (wheel) to the right causes downward deviation of the left aileron and upward deviation of the right one. This gives rise to a pair of controlling forces: one, on the left wing directed upward and the other on the right wing directed downward. The aircraft will roll (turn) with respect to the axis of symmetry to the starboard wing side. On movement of the control stick to the left there will be a reverse effect.

Wheel-type control is usually used on big aircraft with two pilots. The wheel, by its large angle of rotation, enables the "gear ratio" to ailerons to be increased in comparison with that of the control stick, which the pilot cannot move more than 25°. Due to this it is possible with the wheel to transmit a large force to the control member, but at a slower rate of deviation.

The control stick is so made that the pilot is able not only to operate it with one hand but also to carry out at the same time certain other functions such as applying wheel brakes, pressing the trigger of a gun and so on. The other hand is free to control the engines, release the undercarriage, regulate flaps and carry out various other operations.

Foot pedals are as a rule arranged in an identical manner in all aircraft. By pressing a pedal with his foot the pilot turns the aircraft in the required direction. For example, by pressing the right pedal the aircraft is turned to starboard. Each pedal also has a device connected to the wheel brakes and to the steering system of the front or tail wheel.

Due to the development of aviation to high subsonic and supersonic speeds two new circumstances arose.

The first was the increase in the magnitude of the required controlling force with increasing flight speed. The effort necessary to control the aircraft was now such that the physical strength of a man was inadequate for it.

"Boosters" (amplifiers) were therefore installed in the aircraft. In the booster control the pilot does not turn the control members themselves by moving the column, wheel or pedals. He only moves booster valves join-

ing the channels in their casing. Through these channels a special fluid under high pressure from the connected tank enters one or other recess of an actuating cylinder whose plunger is connected with the control member. Thus the effort required from the pilot is only to move a valve while the force necessary to turn the control member is produced by the actuating cylinder.

The second circumstance is the appearance on control surfaces of shocks moving forward or backward depending on the flight speed and angle of attack of the tail plane.

The shocks alter hinge moments, i.e. the moments of aerodynamic forces on the control member about the axis of the hinges on which it turns. This alteration is transmitted to the control stick in the form of a force that is undesirable and, in the case of a large force, inadmissible. The booster, due to its construction, cannot transmit forces from the control member to the control stick. Thus the use of boosters automatically solved these problems. Nowadays boosters are installed on the vast majority of modern aircraft.

Many types of aircraft, mainly those meant for long-range flights under constant regimes, namely passenger aircraft, transport aircraft, bombers, etc., include in their control systems autopilots. These are devices that automatically maintain the set regime of flight, i.e. its altitude, speed and course. After having set the flight regime the pilot switches on the autopilot, which then flies the aircraft.

When partial variation in the flight regime is necessary the pilot can produce it by feeding appropriate data to the autopilot without touching the control stick.

Stability and control members

Ailerons (elevons) situated on the wing and operating in conjuction and on the horizontal and vertical tail planes are the stability and control members.

Ailerons are movable parts of the wing operated by the pilot. They occupy 20–25% of its chord along the width starting from the trailing edge. They are located spanwise nearer to the wing tips. The total area of both the ailerons is 8–10% of the net area of the wing. During their operation ailerons deviate in opposition (one up, one down or both central).

In order to carry out a roll the aircraft must turn through a certain angle about its axis of symmetry. This is possible only if both wings of the aircraft are subjected to lift forces differing in magnitude from what is achieved by only deviating the ailerons.

Thus by deviating the aileron on one wing downward the camber of the wing profile will increase and consequently its c_y coefficient. At the same time the aileron on the other wing will be deviated upward and the camber

of its profile will decrease and so will its c_y. As a result there will arise a difference of moments of the aerodynamic forces with respect to the aircraft's axis of symmetry and it in turn will either increase or reduce the roll already present.

On tailless aircraft there are no stabilizers or elevators. Their functions are transferred to the ailerons. The ailerons are named elevons in this case. They provide not only lateral and longitudinal control of the aircraft but also balance.

This is achieved because the elevons can be deviated not only in opposite directions as ailerons but also simultaneously upward or downward, thus carrying out the functions of elevators. In size they are larger than ailerons.

Longitudinal control of the aircraft, i.e. pitching control, is accomplished by deviating the horizontal tail plane.

Generally the resultant of pressure forces acting on the surface of the wing, fuselage and other parts of the aircraft exposed to the airstream does not pass through the center of mass of the aircraft. As a result a moment of aerodynamic forces arises with respect to the center of mass.

On changing the angle of attack and flight speed the magnitude of the aerodynamic forces is changed as well as the position of the resultant forces and consequently the magnitude of the moment. For the aircraft to fly in a straight line it is necessary to apply to it a balancing moment equal in magnitude, but opposite in direction. To turn the aircraft about the lateral axis it is necessary to apply, in addition to the balancing moment, a control moment. Both these moments are created by the deviation of the horizontal tail plane situated at the rear of the fuselage. It consists of a fixed or movable stabilizer and elevators similar to the wing in construction.

An upward or downward deviation of the elevators changes the camber of the horizontal tail plane profile. This gives rise to a redistribution of pressure over its surface, as a result of which a control force is generated.

At the trailing edge of the elevators are situated small control surfaces —trim tabs which can be deviated upward or downward. A deviation of the trim tab causes corresponding deviation of the elevator. This movement is proportional in magnitude but opposite in direction. By operating the trim tab the pilot can deviate the elevator without touching the control stick. He can select such magnitude of trim tab deviation as will create the necessary balancing moment. The ailerons and rudders are also provided with trim tabs.

At transonic and supersonic speeds the flow around a profile distinctly changes. On the profile appear the shocks dividing the zones of supersonic and subsonic speeds of the airflow around it. This will be described later in detail.

A variation of pressure downstream from a shock cannot propagate

upstream. Therefore if a shock has appeared in front of an elevator or on its leading edge the deviation of the elevator cannot have any effect on the pressure distribution upstream of it, i.e. on the stabilizer. In such a case the pilot can control the aircraft only by deviating the stabilizer.

The location of the horizontal tail plane with respect to the axis of the fuselage has many variants in aircraft construction practice. It is located either below the axis of the fuselage, along it or above it on the fin.

All that has been said about the operation of a horizontal tail plane holds good for a vertical tail plane.

The vertical tail plane consists of a fin (one or more) and rudders. It creates a controlling force to turn the aircraft around the vertical axis (yaw moment) and also provides lateral trim and directional stability to the aircraft. To increase its effectiveness the vertical tail plane of twin or multi-engine aircraft is often multiple so that it is situated in the slipstream from the propellers.

Braking devices

In order to reduce airspeed the pilot decreases the engine thrust. However, due to the low value c_x that an aircraft has at high flight speeds its speed decreases comparatively slowly and over a long distance. In order to reduce the time and distance necessary to drop the speed many aircraft are provided with air brakes which increase c_x by opening or sliding out.

Air brakes are controllable surfaces in the form of flaps, sieves, etc. on fuselages or wings which can be slid into the airstream with the help of actuating cylinders to a magnitude and angle required by the pilot. The brakes' aerodynamic resistance depends on their area and angle of inclination to the airstream.

To reduce speed during the landing run wheel brakes are used. The retarding force of a wheel is equal to the product of the load on it and its coefficient of friction with the ground. The load on the wheel is variable—it is minimal at the beginning of the landing run, since the wing still has a large lift force, and maximum at standstill. The retarding force varies correspondingly.

During landing modern fast aircraft possess such a large amount of kinetic energy that wheel brakes are unable to counteract it over the usable length of runway. Here brake parachutes releasable from the tail end of the aircraft fuselage after touchdown come to their help (Fig. 12).

An aircraft performs its descent and landing with the engines running, i.e. with some thrust present.

Turbojet engines, in comparison with piston engines, have poorer "response," i.e. the capability of switching rapidly from idling to full power. Even at minimum revolutions they can produce quite a large thrust. Thus the use of turbojet engines worsened the landing characte-

ristics of aircraft and accentuated the problem of brake effectiveness.

Many modern aircraft, therefore, have a special turbojet engine in the jet nozzles of which there is an arrangement for reversing thrust. With its

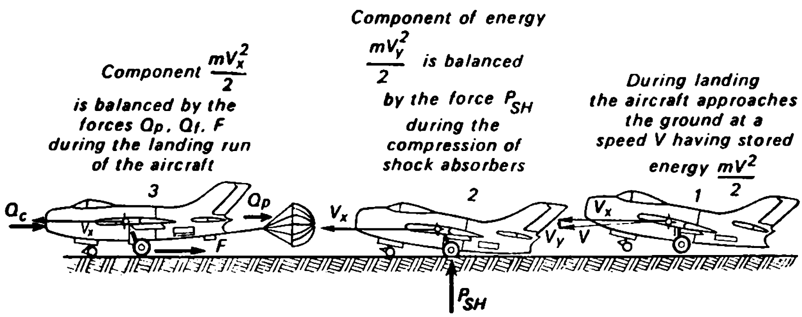


Fig. 12. Forces acting on aircraft during landing.

help the jet of gases is turned forward in the direction of the aircraft's motion. Due to this a reaction force arises which slows the aircraft down. Thanks to thrust reversal two problems are solved together: firstly, in addition to the wheel and air brakes the pilot has at his disposal quite a large controllable retarding force, and secondly, a landing can take place at increased engine revolutions right up to the maximum which is convenient if the need arises for the aircraft to make a second approach. On aircraft with turbo-prop engines the reversed thrust of propellers is used for retardation.

STABILITY AND CONTROLLABILITY OF AIRCRAFT

Concept of stability and controllability of aircraft

The stability of an aircraft is its ability to return to the initial flight regime after its equilibrium has been disturbed. In the presence of disturbances (a gust of wind, dropping of load, etc.) forces and moments acting on the aircraft vary. Generally angles of attack, gliding and rolling and flight speed change. If after being disturbed the aircraft quickly resets by itself to the initial values of the flight regime without the pilot's intervention it is said to have dynamic stability.

If the additional forces and moments appearing as a result of disturbances are so directed that they tend to eliminate the consequences of the disturbance then the aircraft is statically stable.

If these additional forces and moments are so directed that they tend to increase the aftereffects of the disturbances the aircraft is statically unstable.

Thus in considering static stability we are dealing with the nature of

aircraft motion in the first instance after its deviation from the position of equilibrium.

Static stability is a necessary condition for dynamic stability which can be judged only by studying the whole process of disturbed motion.

By the controllability of an aircraft is meant its ability to respond to the pilot's actions through elevator, ailerons and rudder. It is said by pilots of an aircraft that handles well that it "feels good."

High stability with proper choice of sizes of control members and their aerodynamic balance improves the controllability of aircraft and guarantees flight safety.

Factors determining stability

The degree of stability is expressed in terms of the "center of gravity margin," i.e. magnitude and direction of the difference between the actual centering of the aircraft (i.e. the position of its center of mass expressed as a percentage of the mean aerodynamic chord length of the wing[1]) and the neutral centering (i.e. the position of the center of mass where the aircraft ceases to be stable but has not yet become unstable).

The moment of aerodynamic forces with respect to the aircraft's center of mass is made up of the sum of moments of wing, fuselage and engine nacelles on one side and the tail plane moment on the other. The wing moment is characterized by "the turning action" of the lift force. The larger the lift force and the farther from the aircraft's center of mass it is applied, the larger the wing moment. The tail plane moment is the product of lift force developed by the tail plane and its distance from the center of mass. In steady flight all these moments are equal to one another and are mutually balanced.

Besides the center of gravity margin and tail plane power these factors influence stability: position of the center of mass of the aircraft with respect to the chord of the wing along the height, aspect ratios of the wing and the plane, fuselage and engine nacelles, engine performance and so on.

Apart from longitudinal stability an aircraft must also have directional and lateral stability.

Restoring the moments created by the vertical tail plane is the chief means of providing directional stability. Due to them an aircraft, like a wind vane, strives to rise along the airstream and eliminate skidding.

The fuselage, engine nacelles, operating propellers and wing usually create deviating moments, i.e. such moments as tend to increase the skidding already begun.

[1]Mean aerodynamic chord (SAKh) is the chord of a conventional rectangular wing of equal area having the same moment of static stability as that of the wing under consideration.

STRENGTH OF AIRCRAFT

Mass and surface forces

An aircraft is acted upon by two types of forces: mass force and surface forces.

Mass forces are the forces due to the weight of the aircraft parts and the loads situated in it and inertial forces, which are proportional to the mass and act when there is acceleration of every mass element.

Surface forces are aerodynamic forces acting on the surface of the aircraft, engine thrust, forces due to reaction of the ground during taxiing, including take-off and landing, and forces due to interaction of different parts of the aircraft with each other.

The surface forces vary in magnitude with variation in aircraft flight parameters.

Load factor

The ratio of the resultant surface forces to the weight of the aircraft is called the load factor. It is a vector parallel to the direction of the resultant force showing by how many times the resultant of surface forces is greater in magnitude than the weight of the aircraft.

Often only the projection of the total load factor on the axis of the velocity coordinate system is considered. In this system of coordinates axis x is directed in the direction of flight velocity, axis y (axis of the lift) lies in the plane of symmetry of the aircraft and is perpendicular to the axis x, axis z is perpendicular to axis x and y and forms with them a right-hand coordinate system (directed toward the starboard wing). Thus the load factor of an aircraft in the direction of lift n_y is the ratio of the lift to the weight of the aircraft. The load factor in the direction of velocity n_x is the ratio of excess thrust (difference between thrust and drag) to the weight of the aircraft. The load factor in the lateral direction n_z is the ratio of side force to the weight of the aircraft.

The load factor n_y is of utmost importance to aircraft. An aircraft must possess sufficient strength to allow it to carry out all the maneuvers required for the purpose it is designed for within a set lapse of operational time and under the given atmospheric conditions.

Any change in the aircraft motion gives rise to an acceleration of one or the other parameter in a certain direction and is accompanied by the occurrence of large loads.

Besides the loads that appear during maneuvering of the aircraft it also experiences loads during flight through turbulent air. In the atmosphere there are always movements of air at different velocities and in different directions. These airstreams of different strengths, direction and range of action can give rise to large loads on the aircraft.

When hit by an ascending or descending gust of wind the aircraft's velocity is added geometrically to the vertical velocity of the gust. The result is a change in the angle of approach of the airstream toward the aircraft's carrying surface, i.e. a change in the angle of attack, which changes the lift force and sets up a load.

Strength standards

It is difficult to determine in advance the magnitude of maximum loading that an aircraft will experience in flight. Every flight differs functionally from every other. Atmospheric conditions and gusts of wind do not repeat themselves. Besides, the loads acting on the aircraft are complicated and diverse.

To ensure that the aircraft has the necessary strength and adequate design loading there exist strength standards essential for all such structures.

Determinants of strength standards: An adequate degree of strength for various types of aircraft (and other flying machines) is ensured by use of a number of limiting loading parameters: $n^e{}_{max}$ is the maximum operational loading, i.e. permissible loading during operation of aircraft; $n^e{}_{max}$ is the maximum permissible negative loading: $q_{max\ max}$ is the maximum permissible negative velocity head or, in other words, the limiting flight velocity depending on altitude;

Operational, i.e. maximum permissible loading on the main parts of the aircraft during operation;

Factors of safety for the parts of aircraft: Maximum operational loading $n^e{}_{max}$ is the fundamental limiting parameter of loading.

Increase of $n^e{}_{max}$ enhances an aircraft's maneuvering ability, increases its reliability and decreases the possibility of its destruction in flight. However, in this case the weight of the load bearing elements of the aircraft structures increases, leading to a deterioration in other properties and a decrease in flight range and pay load.

Strength standards regulate $n^e{}_{max}$ in accordance with the type and purpose of the aircraft as functions of its weight and the quantity $q_{max\ max}$.

The larger the quantity $q_{max\ max}$ set by the flight-technical requirements of the aircraft and the less its weight, the more $q_{max\ max}$ is built up.

The upper limits of maximum operational loading are established starting from the physical capabilities of an average pilot. It is known from experience that pilots without an overloading suit can withstand for a period of a few seconds the load $n=7$-8, the best trained ones up to 10-12. The overloading suit raises these limits. For this reason $n^e{}_{max}$ for fighter aircraft in different countries is kept in the limits 12-14.

Safety factors

The structural elements of an aircraft are designed for strength on the basis of the ultimate requirement of strength. It is quite natural that the ultimate strength should be that much larger than the maximum operational loading so that when the latter has been reached the structure does not undergo a residual strain, i.e. such strain as would not vanish even after the load was removed.

Residual deformation does not appear in a case where the stresses in a structure that crop up as a result of maximum operational loads do not exceed the stresses corresponding to the limits of proportionality of the material, i.e. the stresses under which the proportionality between the stress and strain has not been exceeded.

For aviation materials the ratio of ultimate stress to the stress corresponding to the limit of proportionality is equal to 1.2—1.4. Therefore strength standards set up a safety factor which is equal to the ratio of ultimate loading to the maximum operational loading or somewhat larger, in the limits 1.5-2.0.

Safety margins are further increased for: a) components which are exposed to considerable stresses in operation, b) components which have to be more rigid, and c) components exposed to heating.

Using strength standards as initial data and tried methods of designing aircraft, the strength of the cross sections of the structural elements of an aircraft is determined with a high degree of reliability.

Testing for strength

Every new, experimental aircraft undergoes componentwise and as a whole static and separate dynamic laboratory tests for strength up to destruction and then tests for strength in flight.

During ground tests the aircraft components are gradually exposed to design loads, their deformations (deflection, twisting) are determined and by means of strain gauges the stresses in structural material are recorded.

When the load corresponding to the maximum operational loading n^e_{max} for a given design point has been reached the structure is unloaded and then the loading for the next design point is taken up. At the end of the tests loading is carried out up to destruction.

During flight tests, apart from recording stresses in the structural elements, the elastic deformation of the structure is also measured.

In addition special tests to determine the aircraft's vibrational characteristics and tests for its reliability under repeated loading are carried out.

HEATING OF AIRCRAFT

Many types of modern aircraft are capable of transonic or supersonic

flight speed. The large velocities necessitate consideration of the heating up of the aircraft.

When air meets the aircraft it is retarded and its kinentic energy is converted into heat. The rise in temperature is proportional to the square of flight velocity. At supersonic velocities the struggle with heating becomes problem No. 1.

The total retardation of air takes place only at certain so-called dead centers of the aircraft (Fig. 3); over the remainder of its surface the movement of air takes place with friction in the boundary layer.

The work of functional forces is converted into heat which heats the air over the surface of the aircraft. The air in turn transfers the heat to the structure. Heating of aircraft surfaces under the effect of friction in the boundary layer makes up on an average nearly 85% of the heating at the point of zero velocity.

Besides aerodynamic heating the power plants, engine exhaust gases, instruments giving out heat during operation and atmospheric and solar radiation can be sources of increasing aircraft temperature. Together with heating the dissipation of heat takes place due to its radiation by the aircraft. However, all the sources of heating mentioned above are important locally, i.e. their effect is limited to a particular region of their location. Up to an altitude of the order of 50 km solar and atmospheric radiation can be totally neglected.

Construction materials react in different ways to the increase of temperature. Some of them withstand a prolonged heating, maintaining their strength, while others are destroyed, or begin to "creep" under loading. Every material has its own coefficients of thermal expansion, thermal conductivity and specific heat.

All these circumstances lead to considerable difficulties in designing high-speed aircraft. First of all it is necessary to decide what material to use for the "hottest" parts of the aircraft. In Fig. 13 are plotted the curves for covering temperatures in degrees Centigrade as a function of altitude and flight velocity. Also shown are the straight lines of maximum permissible temperatures for certain basic aviation materials. It can be seen for what velocities and altitudes of flight these materials are suitable. For example, it is possible to use Duralumin at ground level up to a velocity of 1,500 kmph and at an altitude of 30 km up to 2,600 kmph; titanium alloys up to 3,200 and 4,350 kmph respectively; stainless steel up to 4,150 and 6,600 kmph respectively.

Currently a changeover is taking place from Duralumin construction to construction from steel and heat resistant titanium alloys.

The heating of the surface of the aircraft at high velocities has an adverse effect on the working of aircraft equipment and the reliability of electrical and hydraulic installations. It necessitates safety devices for the crew.

Enormous difficulties are encountered in constructing reliable window glass for the cabins of high-speed aircraft.

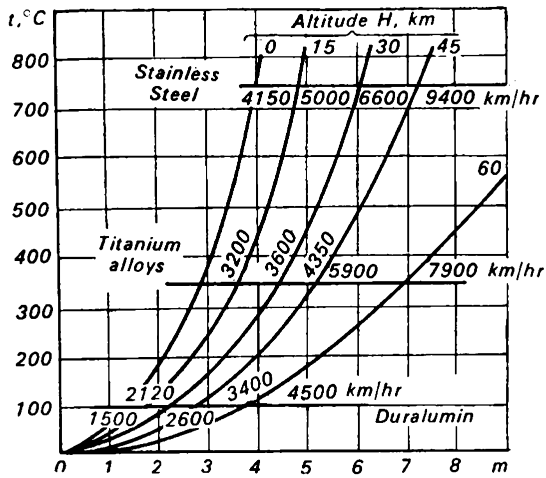


Fig. 13. Temperature of covering.

At present flight at high supersonic velocities is possible only at high altitudes due to the aircraft heating up.

Indeed, for flight at one and the same ground speed at a certain altitude and near the earth the dynamic pressure (velocity head) of air will be of altogether different magnitudes.

An aircraft flying at some altitude experiences a smaller velocity head. One flying near the earth experiences a larger one because the density of air at some altitude is less than that near the earth. When the air strikes a body its kinetic energy, expressed by head, is converted into heat. Consequently an aircraft flying high will generate less heat and its heating will be less than that of an aircraft flying near the earth at the same speed.

ELEMENTS OF AIRCRAFT FLIGHT

The process of flight consists of the following elements: Take-off run, take-off, climbing to level flight (or near to it), maneuvering, descent for landing, landing.

The sequence and frequency of occurrence of the elements of flight from take-off to landing depend on the aim of the flight. In the majority of cases these elements shade into one another quite smoothly without any definite boundaries. The distinct study of each element that follows is arbitrary and for the sake of convenience.

Take-off run and take-off

In the process of the take-off run an aircraft must attain the speed necessary for its separation from the earth, known as "unstick" velocity V_{otr}. This speed is 10–15% more than the level-flight speed at $c_{y\,max}$ with flaps down. This reserve is necessary to provide the aircraft with adequate control and safeguard it from unfavorable effect of a gust of wind.

The take-off run occurs under the action of an accelerating force which is the difference between thrust of the engines developed during the take-off run and the resistance to the aircraft, made up of aerodynamic resistance and frictional resistance of the wheels against the ground.

An aircraft's take-off run is carried out as follows: The pilot taxies the aircraft to the start of the runway, applies the brakes to the wheels and increases engine revolutions up to the maximum. He then gets permission to take-off and then, after releasing the brakes, starts the take-off run. Aircraft with a nose wheel undercarriage complete a considerable part of the take-off run on the three wheels, i.e. with a small angle of attack. After having attained a speed about 0.6–0.75 V_{otr} the pilot raises the aircraft's nose by moving the control stick toward himself. For the rest of the take-off run only the main wheels are in contact with the ground.

Aircraft with tail wheel undercarriages also begin their take-off run on three support points but with a larger angle of attack. Then, by moving the control stick from him the pilot raises the aircraft's tail, transferring the motion to the main wheels.

After unstick velocity has been attained the aircraft separates from the ground. For some time the pilot continues to fly the aircraft near the ground along the path slightly inclined to the horizon and "holds the aircraft."

During this period the speed increases, undercarriage and high-lift devices are retracted. The aircraft soon attains the speed most favorable for ascent and switches over to climbing.

Modern aircraft have a thrust-to-weight ratio (ratio of engine thrust to weight of aircraft) of about 0.6–0.9 and more. Due to this they reach take-off speed very quickly and their take-off run is not excessively long in spite of large take-off loading per square meter of wing area.

The surplus thrust of modern aircraft is so high that it is possible in practice to combine the process of holding with that of climb.

In order to reduce the length of the take-off run boosters are often used. These are special solid-propellant jet engines. They are switched on in the latter half of the take-off run. They work for a period of a few seconds and are turned off after the work is over.

Climb

Climb is straight flight along a path inclined at a certain angle with the horizon.

In this case the aircraft engine has to overcome, besides aerodynamic drag corresponding to the flight speed and angle of attack, a part of the weight of the aircraft, which is equal to the weight of the aircraft multiplied by the sine of the angle of climb (Fig. 14).

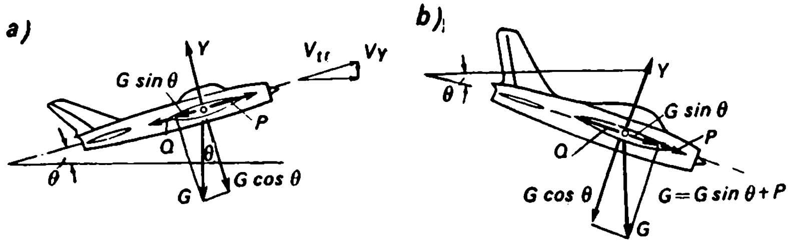


Fig. 14. Forces acting on the aircraft:
a—during a climb; b—during a glide; Y—lift; Q—resistance of air; P—engine thrust; G—weight of the aircraft; θ—angle of flight path inclination.

During a climb the whole of the excess thrust developed by the engine over and above the thrust necessary for level flight goes in overcoming the climb component of the weight of the aircraft. In this case the angle of climb is less than the maximum permissible the excess thrust accelerates the aircraft. The velocity V_{tr} along the path during a climb can be resolved into a velocity parallel to the ground and the vertical one V_y. The magnitude of vertical velocity and the time of climb depending on it are the parameters determining the aircraft's rate of climb.

With the increase in altitude the excess thrust is reduced: the engine thrust declines due to decrease in the density of the air. As a result of this both velocity V_y and angle of climb decrease.

Once the aircraft reaches an altitude where the excess thrust is nearly zero it cannot climb any further. It is then said to have reached the static ceiling. Theoretically at the static ceiling an aircraft can fly with only one speed which is the maximum as also the minimum. An aircrafts' service ceiling is 5–10% less than the theoretical ceiling because if it was limited to one speed the aircraft would be essentially uncontrollable.

Besides the static ceiling there exists a dynamic ceiling which can be reached as follows: At an altitude 2,000–4,000 m below the static ceiling the pilot accelerates the aircraft by diving and then abruptly puts it into a climb. Due to the engine thrust and the kinetic energy obtained during the dive, the aircraft climbs to an altitude higher than the static ceiling but cannot be retained there.

Level flight

Level flight can be without acceleration as uniform motion or with acceleration or retardation as non-uniform motion.

In the first case the thrust of the engines is equal to the drag. In the second case this equality no longer holds. With an excess of thrust over drag an accelerating force is formed. When thrust is less than drag a retarding force is generated. In all cases the aircraft must fly with such angle of attack that the lift is equal to the weight of the aircraft.

The magnitude of acceleration that an aircraft is capable of in level flight as a result of corresponding control characteristic is a property called response, i.e. the ability to change speed.

Maneuvering

Maneuvering is the flight of an aircraft along a complex of trajectories. A curvilinear motion occurs in every flight. In some cases it is necessary only to change the direction of flight in horizontal, vertical or both planes together, while in other cases (for example in military aircraft) maneuvering is the basic battle characteristic.

Maneuvering in air battle is a whole cascade of aerobatic figures where the flight takes place along spatial (three-dimensional) curvilinear trajectories and is accompanied by the aircraft's rotation about the longitudinal axis. The most widespread and best known aerobatics are: Nesterov loop, combat turn, half-turn and roll, half-roll, roll, spinning dive, spin.

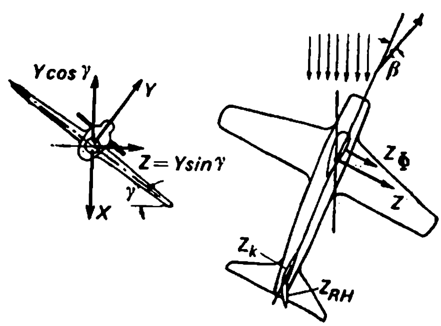


Fig. 15. Rise of centripetal force in the horizontal plane:

a—during banking of aircraft; b—during skidding of aircraft; Z—centripetal force; γ—angle of bank; β—angle of skid; Z_ϕ—centripetal force of fuselage; Z_k—centripetal force of the fin; Z_{RH}—centripetal force of rudder.

The maneuvering qualities of an aircraft are characterized by the radius and duration of bank, i.e. the aircraft's turning ability, response, vertical velocity and the amount of overloading it can withstand.

To carry out a curvilinear flight a force directed perpendicular to the trajectory of motion is necessary. Thus to deflect the aircraft's path in a vertical plane it is necessary to have excess lift over the weight. To deflect its path in a horizontal plane a force lying in the same plane has to intervene. This force can be obtained as a result of either yawing or banking. In the first case it will be the force due to air pressure on the side surface of the fuselage and the fin lying in the horizontal plane and in the second case it will be the projection of the wing's lift in the horizontal plane (Fig. 15).

The most typical path of a curvilinear flight in the horizontal plane is a banked turn by the aircraft. A properly banked turn is flight in the horizontal plane along a curve of constant radius with a constant angle of attack, constant speed and no yawing.

Descent

Descent or gliding by an aircraft is carried out with the engine working at low rpm (in the idling area).

The path of an aircraft during descent is inclined at some angle θ (Fig. 14b) with the horizon. In the absence of engine thrust the lift is equal to the weight of the aircraft multiplied by the cosine of angle θ, while the drag is equal to the weight of the aircraft multiplied by the sine of angle θ.

The power necessary for the aircraft's motion along the glide-path and for overcoming the forces of air resistance set up by the glide are created by the potential energy of the gravitational force and engine thrust.

The range of an aircraft glide depends on the altitude at which the glide starts and the lift-to-drag ratio. It is equal (without taking into account the wind and engine thrust) to the product of the altitude and the aircraft's lift-to-drag ratio.

A descent with the engines running makes it possible to vary the angle of descent and to "stretch" the aircraft in case of a faulty landing approach or the need to go around for another approach.

As he approaches the airfield, having obtained clearance to land, the pilot executes maneuvers for landing on the runway and releases the undercarriage and landing flaps. He regulates the flight speed and angle of descent by changing the angle of attack and engine thrust and steers the aircraft toward the ground. He then gradually transfers the aircraft from the inclined path to a level path parallel to the ground.

After leveling the aircraft the pilot holds it off at a height of about 1 m above the ground. The flight speed is then reduced and at this the pilot increases the angle of attack, thus raising c_y of the wing.

When the angle of attack reaches the maximum permissible value for landing for a particular type of aircraft, c_y does not increase further. The aircraft begins to fall and touches the ground with its wheels. The speed of the aircraft at the moment of touching the ground (touchdown) is called the landing speed.

Landing

The landing speed depends on $c_{y_{\text{pos}}}$—c_y at the time of touchdown and the wing loading coefficient $c_{y_{\text{pos}}}$ is determined not only by the wing's lift-to-drag ratio but also by its landing angle. This angle is equal to the sum of the angle of the wing setting and the angle at which the axis of the aircraft is inclined to the ground. It is usually within the limits of 10–15° and

sometimes smaller. The angle between the wing-chord and the aircraft's longitudinal axis (setting angle) is so chosen that in the most typical flight regime for the aircraft its longitudinal axis remains horizontal and the fuselage has minimum resistance. For high speed aircraft this angle is unimportant.

At the time of touchdown the aircraft possesses enormous kinetic energy equal to half the product of the mass of the aircraft and the square of the landing speed. Modern aircraft are many times heavier than their predecessors. According to foreign press reports the modern fighter aircraft weighs from 5 to 15 tons. Bombers were that heavy only by the end of the Great Patriotic War and fighter aircraft weighed 3–4 tons. Landing speeds have since doubled. Correspondingly the kinetic energy of landing aircraft steeply increased. This must be dissipated during the aircraft's landing run by braking devices.

For aircraft having a large thrust-to-weight ratio the length of the landing run considerably exceeds the length of the take-off run. If pilot error is also taken into account then it is the length of the landing run, more accurately the landing distance, and not the length of the take-off run that determines the length of runways required for airdromes.

Landing distance is the distance that an aircraft travels during landing from the point where it is at a height of 25 m to standstill, i.e. a distance that includes the end of leveling, hold-off, touchdown and landing run. Correspondingly the take-off distance includes the take-off run, hold-off and climb to 25 m.

PHYSICAL PICTURE OF FLOW AROUND THE WING AT HIGH FLIGHT SPEEDS

Velocity of sound

The speed of the pressure of sound oscillations in any medium varies with its density. These perturbations are transmitted with the speed of sound propagation in the medium. In a gaseous medium only longitudinal waves developed during compressions and expansions of the gas can be propagated. The speed of sound depends on the temperature of the gas and is proportional to the square root of its absolute temperature. At the temperature of 15°C the speed of sound (denoted by the latter a) in stagnant air is 341 m/sec$=$1,228 kmph. In the stratosphere temperature is constant (-56.5°C) and therefore the speed of sound is also constant. It is 295 m/sec.

In practical aerodynamics the ratio of the speed of flight to the speed of sound is denoted by the letter M so that $M=V/a$. When the flight speed approaches the speed of sound the compressibility of air begins to show its effect and its density changes.

Basic types of motion of compressible medium

There exist three basic types of motion of a compressible medium like air, namely:

1) velocity of air less than the speed of sound. This is the region of subsonic velocities ($M < 1$). In this case an increase in the cross-sectional area of the flow results in a decrease in the velocity and, correspondingly, a rise in its pressure, while a decrease in the cross-sectional area increases velocity and reduces pressure;

2) velocity of air equal to the speed of sound, i.e. $M = 1$. In any compressible medium the flow velocity can reach the speed of sound only at the point of minimum cross section;

3) velocity of air in excess of the speed of sound, i.e. $M > 1$. This is the region of supersonic velocities.

In supersonic flow the velocity is increased only by increasing the cross-sectional area of flow. In this the gas expands in such a fashion that the flow velocity increases with the simultaneous decrease in density and static pressure of the gas. The decrease in the cross section of flow decreases its velocity and increases its pressure and density. Thus in supersonic flows a picture opposite to the one typical of subsonic flows is observed. These distinctions in physical pictures of the motion of a stream of compressible gas (air) give rise to difficulty in studying the flow in the transonic region when a transition of flow from subsonic velocities to supersonic velocities and the reverse takes place.

Let us define various speeds.

The speed of propagation of sound waves in a medium is called the speed of sound.

The local speed of sound is the speed of sound in the flow corresponding to the temperature of the point under consideration.

A flow speed where the speed of the air particles does not exceed the speed of sound at any point in the flow is called a subsonic speed.

Flow speeds which exceed the one where at any point of the flow a speed equal to the local speed of sound has been reached but are less than the speed at which the whole flow becomes supersonic, are called transonic speeds.

Supersonic speed is a flow speed at which at all points of the flow the local speed is more than the speed of sound.

Hypersonic speed is one that exceeds the speed of sound by more than four or five times.

The patterns of flow over a body moving at a speed less than that of sound and over one moving at supersonic speed are not identical.

In a subsonic flow around an airfoil the airstream begins to divide even before it has, so to speak, received notice of the approach of a body. It adjusts to the flow around the body in advance. The signal is the rise in pressure propagating with the speed of sound from the leading edge of the

airfoil. This happens because the speed of propagation of the increased pressure is more than that of the body itself.

If the speed of the body exceeds the speed of sound any deformation of the flow cannot take place in front of the body and the body cuts its way into totally undisturbed flow. Clear-cut boundaries separating the undisturbed region from the region disturbed by the body occur.

The appearance of such boundaries is explained as a mutual superimposition of continuously arising spherical waves of increased pressure from the leading edge of the body.

Let the source of disturbance *1* (Fig. 16a) be stationary with respect to the medium. In this case it will coincide with the center of the waves propagating in the form of concentric spherical surfaces. The radius of every sound wave increases proportionally with time by a quantum equal to the speed of sound.

If the source of disturbance moves with a subsonic velocity (Fig. 16b) the front of all waves increases its distance from the source with a velocity equal to the difference between the speed of sound and that of the source which, therefore, remains inside the sound circles.

If the source moves with the velocity of sound (Fig. 16c) its velocity and the speed of the wave front are equal. The waves do not outdistance the source. In course of time the sound circles increase and gradually approach a straight line perpendicular to the direction of the motion of the source and

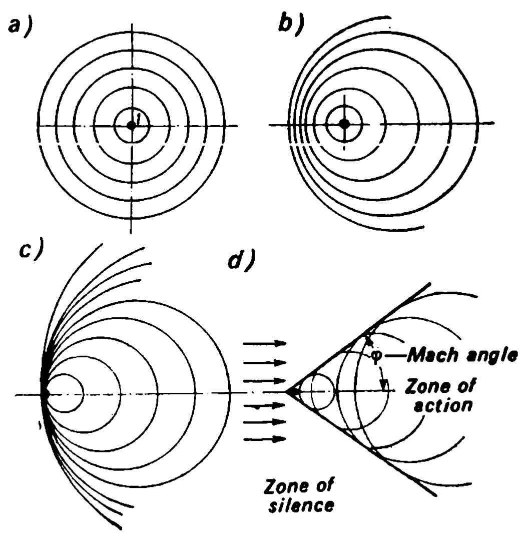


Fig. 16. Modes of propagation of disturbances from a point source:

a—source of disturbances stationary ($M = 0$)*; b—source moving with subsonic velocity* ($M < 1$)*; c—source of disturbances moving with the speed of sound* ($M = 1$)*; d—the source leaves the sound wave behind.*

form a normal shock. The source of disturbances lies on the wave front all the time.

Finally, if the source of disturbances moves with supersonic velocity (Fig. 16d) it moves through the waves it has created and outdistances them. Oblique shocks form inclined at an angle determined by the ratio of the velocity of the source to the speed of sound indicated by the symbol M.

The sine of this angle is called the limiting angle of perturbation or Mach angle and is equal to 1/M.

The radius of sound waves left behind increases proportionally with time.

The spherical waves therefore fill a certain volume behind the source in the form of a cone called a Mach cone with its apex coinciding with the source.

The surface of the cone forms a boundary between the free, undisturbed flow and the region of the disturbed flow. This discontinuity in the flow is the distinctive feature of supersonic flow.

Flow past an airfoil

Now we will briefly study the flow of a compressible gas past an airfoil and the formation of shock waves (Fig. 17).

No qualitative variations in the flow pattern are observed unless the flow velocity attains the speed of sound at a certain point.

Local values of M in a totally subsonic flow are everywhere less than unity. Flight M number at which the speed of sound is reached for the first time at some point in the stream is called the critical number, M_{cr}.

At some point *1* (Fig. 17a) on the upper surface of the airfoil the flow of air for the first time reaches the speed of sound. The pressure perturbations propagating from this point with the speed of sound form a front of pressure waves which on meeting with the flow of air gives rise to a pressure surge and a shock wave is formed.

In the beginning the shock wave is formed on the upper surface of the airfoil near the point where the pressure is minimum. With an increase in the M number the shock wave becomes more distinct and gradually moves backward toward the trailing edge.

During this increase in the M number the turbulence intensifies the separation of the boundary layer behind it. After reaching the speed of sound a shock wave also forms on the lower surface of the airfoil but nearer the trailing edge.

Shock waves and pressure surges bring about variations in the lift, a sudden increase in resistance and a change in the distribution of pressure along the airfoil.

This leads to intense, nonuniform and irregular distribution of pressure which affects the aircraft's stability at transonic velocities.

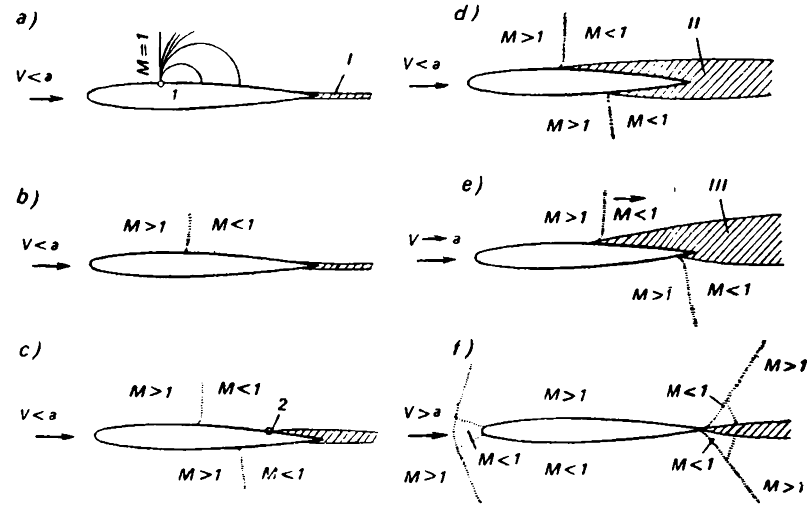


Fig. 17. Development of shock waves and spasmodic flow separation behind the shock wave with increase in M number:

a—local velocity attains the speed of sound at point 1; b—shock wave is formed on the upper surface of the airfoil without flow separation; c—shock wave is formed on the lower surface of the airfoil, flow separation begins at point 2; d—flow separates from under the shock; e—shock waves move toward the trailing edge of the airfoil at M $\geqslant$ 0.8; f—leading edge shock wave is formed in supersonic flow; I—trail; II—region of separated flow and turbulent air; III—region of highly turbulent air.

At high subsonic velocities (M $\geqslant$ 0.8) shock waves are nearly perpendicular to the surface of the airfoil. On transition to supersonic flight velocity shock waves on both sides of the airfoil reach the trailing edge and are inclined backward at an angle depending on the M number. In front of the leading edge a new shock wave is formed called leading edge shock wave.

At subsonic flight velocities the leading edge wave always outdistances the flying body. During the transition of flight velocity through the speed of sound the leading wave begins to draw nearer to the leading edge of the body. At high M numbers it clings to it.

If the leading edge is sharp the leading edge shock wave comes right off the leading edge.

With increasing flight velocity the leading edge shock wave and the shock waves at the trailing edge bevel up and meet in a more acute angle.

Shock stall and wave drag

We will consider the case of a flow where a supersonic zone is formed only on the upper surface of the wing. Behind the point at which the speed of sound has been reached an expansion zone is developed with

increasing flight velocity. This brings about a notable rise in both lift and drag. The latter can be explained by the fact that the expansion of air behind the maximum thickness of the wing is more than that in front, which gives rise to a force directed backward, i.e. to an additional resistance.

Upon formation of a zone of supersonic velocity on the lower surface of the wing, besides the increase in drag, the rate of growth of coefficient of lift c_y is reduced. It then decreases considerably.

The additional drag due to the presence of a supersonic zone on the airfoil is called wave drag.

A local supersonic zone passes into a subsonic one not by smooth retardation but with a shock which is the boundary of transition of a supersonic flow of low density into a more dense subsonic one. This transition involves a loss of energy spent in heating of the air during compression.

The transition of supersonic velocity to subsonic velocity is essential because the velocity of the wing under consideration has not yet reached the speed of sound and somewhere near the trailing edge of the wing the velocity of the flow must return to a subsonic value.

The thickness and camber of an airfoil largely govern the quantity M_{cr}.

If they are reduced M_{cr} increases, i.e. the flow regime involving the presence of a supersonic zone or, as it is sometimes called, "the wave stall" develops later.

Flow at supersonic flight velocities

As has already been said, at supersonic flight velocities the flow velocity at any and all points of the airfoil (local velocity) is a supersonic one. From leading edge to trailing edge there are shock waves inclined at angles which depend on the M number.

Pressure perturbations caused by the airfoil's camber and angle of attack are propagated only inside the Mach angle. Therefore the field of perturbations above the airfoil is determined solely by the shape of the upper surface and that beneath the airfoil by the shape of the lower surface.

Pressure at any point of the surface does not depend on the pressure at neighboring points. It is proportional to the angle made by a tangent to the airfoil at the point under consideration with the direction of undisturbed flow, i.e. with the direction of flight.

The distribution of pressure over the surface of the airfoil at zero angle of attack (zero angle pressure distribution) depends solely on the shape of airfoil. At a certain angle of attack to the zero angle additional pressure distribution is added. This is called carrier pressure distribution. It has a constant value over the whole chord length and is proportional to the angle of attack.

At a positive angle of attack carrier pressure over the lower surface is greater than on the upper surface, at a negative angle of attack the situation is reversed.

The resultant distribution of pressure is the sum of the zero angle and the separate carrier pressures of the upper and lower surfaces.

Experience has shown that in the case of supersonic airfoils the lift at supersonic velocities is created mainly by the excess of pressure over the lower surface.

The coefficient of lift c_y in the case of a supersonic flow around the airfoil is strictly proportional to the angle of attack and does not depend on the shape of the airfoil.

Airfoil camber does not affect lift (unlike with a subsonic flow). With an increasing M number the coefficient of lift drops. In subsonic flight (at low velocities) it does not depend on velocity. Drag in the supersonic flow is made up of wave drag, frictional drag and profile drag.

Wave drag arising due to the continuous formation of pressure waves at supersonic velocities is determined by the energy spent in forming them. It is proportional to the square of the angle of attack and is thus closely associated with the lift at supersonic velocities. It also depends on the strength, shape and number of shock waves and their position with respect to the airfoil.

Profile drag is the sum of the projections of pressure forces in the direction of velocity. It depends on the thickness of the airfoil and is proportional to the square of the relative thickness. The profile drag of a flat plate is equal to zero. A symmetrical diamond-shaped airfoil has the minimum profile drag among airfoils of a given thickness. The position of the center of pressure for all symmetrical airfoils at supersonic flight velocities is the same, namely in the center of the airfoil chord. At below-critical subsonic velocities it is located at a distance of about one-fourth the breadth of the airfoil behind the leading edge.

The coefficient of profile drag for supersonic airfoils decreases with an increase in the M number.

At one time the large growth of drag force due to the occurrence of shock waves, undesirable phenomena connected with the worsening of aircraft stability that might cause it to go into a dive due to the shifting of the center of pressure backward and variations in the effectiveness of the horizontal tail plane, gave rise to the view that aviation had met the limits of airspeed in what is called the "sound barrier."

However, the study of physical phenomena occurring in an airstream flowing around a body at transonic and supersonic velocities and the data of model tests in supersonic wind tunnels led to the development of techniques not only to delay the beginning of "wave stall" but also to reduce considerably the growth of wave drag. The apparently insurmountable

"sound barrier" was successfully overcome or to put it figuratively, moved, filled and smoothed out.

Here are the basic recommendations based on the results of the investigations:

a) use of relatively thin airfoils for wings and tail units with the maximum thickness shifted to about 40% of the chord, having a small radius of curvature at the leading edge (sharp leading edge), a thin profile behind (small angle at the trailing edge), small curvature of center line and a perfectly smooth surface;

b) making the wing swept-back (arrowhead) in plan;

c) use of wings with low aspect ratio, including delta-shaped wings.

Use of swept-back wings is necessitated by the following: Firstly, considering a swept-back wing as a rectangular one merely inclined to the flow direction, we see that the relative thickness of its cross section directed along the flow is less than that of a straight wing by the cosine of sweep angle. This is a favorable factor.

Secondly, in the case of swept-back wing the lines joining the beginning and end of local supersonic zones in the wing sections are inclined with respect to the flow, as a result of which the pressure waves formed are not normal but oblique ones, i.e. less intense.

And thirdly, the span of a swept-back wing is less than that of a conventional one of the same area and the reduction of aspect ratio, as experience shows, is also favorable.

It has been experimentally proved (Fig. 18) that swept-back wings have considerably lower drag at high subsonic velocities than straight wings of the same profile. At transonic and supersonic velocities the magnitude of sweep of the leading edge becomes a determining factor while the sweep of the trailing edge is comparatively less important.

Apart from sweep the other factor that results in increase of M_{cr} and delays the effect of compressibility of the air is lowering of the wing aspect ratio, i.e. the ratio of the wing's span to its mean geometric chord. On decreasing the aspect ratio for the same area the chord of the profile increases. This makes it possible to use relatively thinner profiles having a high M_{cr} number.

The flow around a wing of a low aspect ratio is no longer a purely two-dimensional one: it approaches the three-dimensional and is accompanied by changes in critical velocity and sloping of pressure waves.

For a wing of low aspect ratio (including delta-shaped) with a beveled leading edge it is the sweep of the leading edge that is all-important.

Theory and experience show that:

a) a low below-critical velocities ($M \approx 0.6$; $V \approx 720$ kmph) straight wings have the minimum drag;

b) after reaching the critical numbers ($M \approx 0.6$ to 0.8) a little sweep

delays the moment of arrival of shock waves and reduces the drag;

c) transonic velocities (M $\approx$ 0.8 to 1.2; $V \approx$ 950 to 1,400 kmph) demand a large sweep λ = 30 to 45°;

d) at supersonic velocity (M > 1.2; V > 1,400 kmph at ground level) it is necessary to give the wing a sweep of about 60° or more, giving it the shape of a triangle.

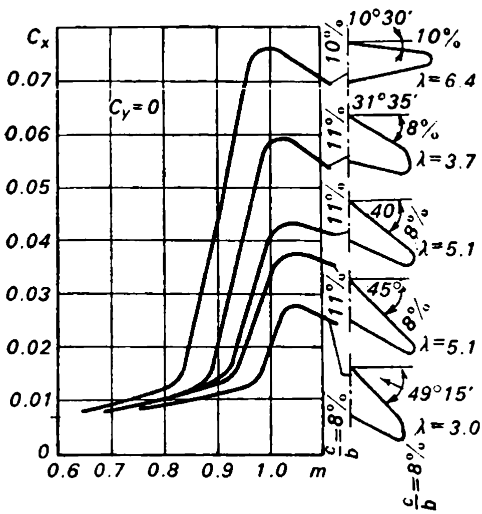


Fig. 18. Effect of sweep back and aspect ratio of the wing on its resistance in the transonic region:

$\lambda = \dfrac{L}{b_{mean}}$ —*wing aspect ratio; L—wing span;* b_{mean}—*mean chord of the wing;* $\dfrac{b}{c}$ —*optimum thickness of the wing; c—thickness of the wing; b—chord of the wing.*

TYPES OF AIRCRAFT

The tasks that aircraft can handle are extremely diverse and for their fulfillment conflicting construction requirements are very often essential. Every type of aircraft is designed and built to carry out only those specific tasks for which it is designed. This led to the specialization of aircraft and a diversity of types.

We will consider below the purpose of various types of aircraft and their basic types and detail their main requirements, why they are necessary and how these types of aircraft have developed in recent years.

We will also consider the principles of construction and working of a helicopter, rotary wing aircraft, tailless aircraft, short and vertical take-off and landing aircraft and aircraft with variable geometry wings.

In conclusion we will look into the possibility of creating hypersonic

aircraft.

First of all aircraft are divided into civil aircraft and military aircraft. Military aircraft in their turn are subdivided into fighters, consisting of two basic groups: interceptors and fighter bombers; bombers of various flight ranges, reconnaissance aircraft, special purpose aircraft, military transport aircraft and aircraft for various auxiliary purposes.

Naval aircraft are subdivided according to their basing into shore-based and ship-based aircraft.

Fighters

We will begin with the interceptor. It is meant for interception and destruction in the air of enemy aircraft and unmanned enemy air devices.

An interceptor must take off at minimum notice after detection and identification of an approaching enemy by the ground radar stations, climb to the altitude of free maneuver higher than the enemy's, reach the limit of interception, i.e. the boundary beyond which the enemy must not penetrate, enter the zone from where attack will be effective and then attack and destroy the target.

It must therefore have a complex of the highest flight qualities in their optimum combination: a fast rate of climb, high ceiling, maximum speed, excellent maneuverability and powerful armament.

The latest achievements in aviation science and engineering abroad are in the first instance embodied in the interceptor. The modern equipment and armament which it is provided with enable it at any time of day, irrespective of weather conditions, to attack the target and destroy it with a high degree of probability.

The evolution of the interceptor and variations in its constructional shapes clearly demonstrate the development and achievements of aviation science and engineering during the last 20–25 years.

Jet engines were first mounted on interceptors. Thanks to this it approached the sound barrier. When thinner, beveled wings were introduced it overcame this barrier and soon began to move into the region of supersonic velocities.

The changeover to wings of low aspects ratio with special thin profiles, delta-shaped wings in particular, made it possible to achieve velocities up to 2.5 M and more. At such velocities it is quite impossible to fight a battle "visually." Rates of approach and turn have become so great that opponents in battle simply do not see each other, or they come into each other's field of vision only for fractions of a second.

It thus became necessary to provide interceptors with special surveillance and fire control radar systems to enable them to detect and identify the enemy at tens of kilometers, to lead them automatically to the zone of possible attack and open fire with the armament on board . Interceptors are

also fitted with special equipment to solve navigation problems with a high degree of reliability, guarantee flight in any weather conditions, guide them to their own airfield, assist in landing and maintain dependable communications with command posts and guidance stations.

The changeover of the armament from cannon to guided homing "air-to-air"-type missiles took place. Homing missiles launched toward a target "lock" onto it with the help of a "homing" device located in the nose and approach it. A computer works out signals from the homing device about the coordinates of the object and transmits commands to the controls. After approaching to within a calculated distance from the target the missile explodes and disables it.

As the problems of interception became more complicated it became necessary to devote intense care to detection and destruction of the target. The power of the engines was increased and correspondingly the absolute weight of the fuel necessary for flight also increased. All this led to an increase in the take-off load of interceptors.

Even at the time of the Patriotic War the high mobility of troops, the strengthening of their protection from air attack, dispersal and camouflage divided the operational tactics for attacking ground targets into: operations from high and medium altitudes over an area occupied by enemy troops and operations from low altitudes over small-sized targets. The latter tasks are carried out by the attack aircacft Il–2.

With increasing flight speeds and the development of radar interceptors the scope for a second class of tasks became evident. A new type of fighter aircraft appeared—the fighter-bomber.

A fighter-bomber possesses the qualities of a fighter aircraft designed to take on aerial targets together with the ability to destroy ground targets.

It is necessary for a fighter-bomber to fly at low altitudes as ground radar stations can detect at long ranges only objects flying fairly high.

If the aircraft is flying at a high altitude and if the ground target is camouflaged it is difficult to detect it well in advance. To take care of such targets the fighter-bomber possesses bombs and "air-to-surface" missiles as well as cannon.

It was also required to develop special equipment to pilot the aircraft automatically at a given low altitude and operate the navigational and fire-control systems and target detection equipment.

A fighter-bomber is designed taking into consideration the large stresses arising during flights at high speed at low altitudes.

For example, at $M = 1.5$ at ground level the velocity head exerts a force of 16 tons per square meter of surface.

Bombers

Bombers are aircraft meant for carrying out bombing attacks on land

or sea targets or for use as unmanned carriers for "air-to-surface"-type missiles. Bombers are subdivided into short-range (tactical) and long-range (strategic) bombers depending on their flight range. A tactical bomber usually operates over area targets in the vicinity of front-line operations.

Long-range bombers are intended to destroy from the air targets of strategic importance located deep in enemy territory.

To be secure against destruction during flight over enemy territory and during the bombing operation modern bombers must not differ greatly from fighters in flight altitude and speed.

Creation of "air-to-surface"-type stand-off rocket missiles with powerful nuclear warheads and a high flight speed which can be slung under the bombers enables them to destroy ground targets without entering the enemy's air defense zone.

During their development bombers had to overcome the same difficulties as the fighters, only more complicated due to the larger dimensions. The aerodynamic and construction shapes of modern bombers and fighters are more or less similar.

Reconnaissance aircraft

A reconnaissance aircraft is a specially designed or equipped aircraft of another type intended to carry out air reconnaissance. It is provided with a variety of photographic equipment for aerophotography and similar up-to-date means of reconnaissance.

In order to destroy a target by missile it is of course necessary to know where it is located, i.e. it is necessary to reconnoiter the target and determine its exact coordinates or, as they say, "to tie down the target."

According to foreign literature, building a good reconnaissance aircraft is a complicated task because it must have a long range and high flight altitude with the crew and equipment aboard, and must also have the ability to develop a high speed to elude enemy fighters.

The difficulties in building a manned reconnaissance aircraft, with a high probability of destruction by enemy fighters, since it usually operates alone, or by "surface-to-air" missiles, gave rise abroad to the construction of unmanned reconnaissance aircraft.

The take-off and landing of such aircraft is carried out by radio commands, while the flight along the programmed course is achieved with the help of automatic control equipment and an autopilot.

By using unmanned aircraft the necessity of training crew whose chances of survival are very low is eliminated.

Military transport aircraft

The tasks handled by military transport aviation are: paradropping of

troops (parachute landing), transportation and landing directly on the ground of troops and military equipment (airborne landing) and transportation of all kinds of military cargo.

Military transport aircraft have undergone radical changes in recent years. They have started to use turbo-prop engines which have increased the load lifting capacity and maximum flight speed. Transport aircraft grew considerably in size, enabling them to accommodate large landing subdivisions with armament and equipment. It became possible to carry out the airborne or parachute landing of large-sized equipment of high hitting power including medium tanks.

Modern assault transport aircraft can take off from unpaved airfields and their equipment allows them to fly in difficult weather conditions.

Civil aircraft

Civil aircraft carry out a variety of economic tasks. They transport passengers and freight not only within the boundaries of our motherland but also on international routes linking the USSR with more than 60 foreign countries.

During the post-war period piston engine aircraft were replaced with turbojet and turboprop (TRD and TVD) aircraft: the Tu-104, Tu-114, Tu-124, Tu-134, Yak-40, Il-18, Il-62, An-12, An-14, An-24.

Aircraft with TRD have a cruising speed of 850–900 kmph and those with TVD from 650 to 800 kmph, i.e. two to three times that of Li-2 and Il-14 aircraft with piston engines. Besides the increase in flight speed the switch to TRD and TVD resulted in an increase in load lifting capacity.

Modern airliners carry from 100 to 200 passengers in their comfortable pressurized cabins. They carry the most valuable load—people. The designers therefore do their utmost to make these aircraft especially reliable so that they function regularly according to schedule.

The aircraft are provided with special equipment which with the help of equipment at airports and along the routes ensures not only flight in any kind of weather but also safe landings in difficult conditions, even in zero visibility right to touchdown.

According to use passenger aircraft are subdivided into trunk route and short-haul aircraft. The latter are comparatively small aircraft serving those populated localities situated away from the main air routes. They must operate from small-size airdromes without concrete runways. On local air routes the piston engined aircraft An-2, Li-2 and Il-14 are still being successfully operated.

Apart from transporting passengers and freight civil aircraft assist agriculture by aerial spraying with chemicals and feeding of crops with chemical fertilizers; protect forests from fire; carry out aerial reconnaissance for fish; watch the movement of ice in the Arctic and help maritime operations;

carry out geological surveys; serve scientific research and survey expeditions; conduct air-ambulance services, rushing doctors to isolated almost inaccessible places and transporting the sick.

To fulfill these functions usually the same trunk and short-haul aircraft are used which are specially adapted and provided with suitable equipment.

Trainer aircraft (initial flying training) and sports aircraft are separate classes of civil aircraft.

In recent years, the development of a supersonic passenger aircraft has been in full swing. Various construction arrangements are being investigated, aerodynamic shapes are being studied, special engines are being designed, means and methods of protection from aerodynamic heating are being devised and so on. Problems like the altitudes and speeds such aircraft must fly at, what the range must be and so on are being discussed.

It is now accepted in most countries that from an economic point of view, i.e. taking into account the cost of its construction, its operational expenses and expected revenue earning it is advisable to design supersonic passenger aircraft for a range of 5,000 km at a flight speed of 2.2 to 2.5 M.

The published photographs of the supersonic passenger aircraft Tu–144 worked out by a team of designers led by A.N. Tupolev give an idea of the shape of such an aircraft.

HELICOPTERS

In modern aviation helicopters are now being more widely used. This story would be incomplete if at least a brief run-down were not given on helicopters.

The helicopter is a flying vehicle having one or more rotors (propellers) of a large diameter which create lift and thrust for motion.

A helicopter can take off vertically, remain still in the air and move in any direction.

The main rotor has three or more blades fixed on a common central hub in such a way that they can vary the angle of attack and move within certain limits in vertical and horizontal planes. The extent of deviation of the blades is limited by stops.

A suspension joint arrangement and mechanical links joining the blades with each other provide the transmission of the turning moment from the shaft of the reduction gear to the blades through the rotor hub.

While in rotation the blades deform the airflow and push it downward. In line with the law of conservation of momentum the helicopter, by pushing downward and comparatively low velocities a large mass of air swept by the rotor, receives the same amount of momentum itself but in an upward direction, equal to the product of the helicopter's mass and the vertical velocity imparted to it.

During the rotation of a blade hinged to the rotor hub the forces acting on it are the aerodynamic forces, the weight of the blade itself and centrifugal force.

The resultant of these aerodynamic forces can be resolved into three forces: a force parallel to the axis of rotation of the blade, a force of resistance to the blade motion lying in the plane of the blade and a force directed along the blade. The first of these forces is the lift developed by the blade.

The helicopter in its entirety appears as if suspended from the main rotor.

In the stationary position the blades of a helicopter's main rotor resting on their hinges droop downward. At this point the blade's center of gravity is situated below the plane in which the suspension hinges lie. As soon as the blade starts to turn centrifugal force arises and its moment about the plane of the hinges straightens the blade out.

With increasing circumferential speed and increasing lift the blade is deviated upward more and more. As soon as the plane of rotation of the blade's center of gravity passes through the plane in which the suspension hinges are situated the moment due to centrifugal force changes its direction and begins to oppose the blade's deviation upward. In motion the blades describe a cone that varies its apex angle all the time during flight.

To rotate the main rotor a turning moment is applied to it through a reduction gear. In line with the law of equality of action and reaction a moment arises in the reduction gear equal in magnitude but opposite in direction which tends to twist the helicopter. On the ground this reaction moment is balanced by the reaction of the ground under the wheels. But what about it in the air?

Designers solved this problem by two devices. In the first method another rotor was fixed on the tail boom of the helicopter. This was linked mechanically to the reduction gear of the main rotor (Fig. 19). The plane of rotation of the tail rotor is parallel to the plane of symmetry of the helicopter. During its rotation a moment is generated equal to the product of the rotor thrust and the length of the arm up to the axis of the main rotor. By varying the pitch of the tail rotor the pilot obtains an additional moment that will turn the helicopter in the required direction.

The second method is by use of coaxial main rotors or rotors situated one behind the other rotating in opposite directions (Fig. 20b, c, d). In this case the turning moments from the rotors will be opposite signs to each other and consequently will eliminate one another.

During a helicopter's ascent or descent in a vertical direction, i.e. during a flight without translatory speed, the blades of the main rotor are under identical conditions in respect of their turning motion. If the helicopter acquires a translatory speed (velocity) the aerodynamic picture of the

working of the blades becomes a different and fairly complicated one.

A blade moving forward in the direction of flight receives relative to the air an additional velocity equal to the flight velocity while the velocity

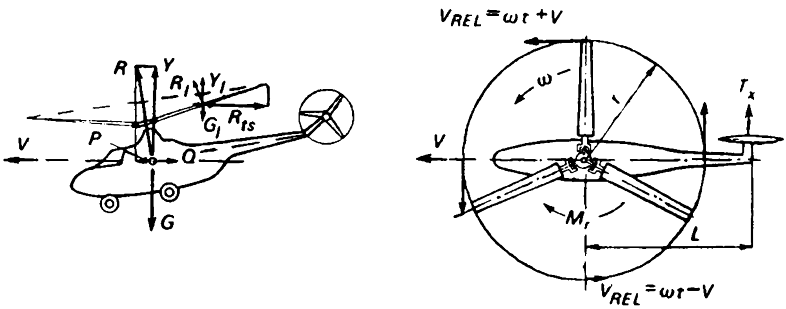


Fig. 19. Basic forces acting on a helicopter:

R_1—resultant of aerodynamic forces of the blade; G_1—weight of the blade; R_{ts}—centrifugal force of the blade; Y_1—lift of the blade; R—resultant of aerodynamic forces of the main rotor; Y—ascending force of the main rotor; P—thrust of the main rotor; G—weight of the helicopter; Q—the resistance of air to motion of the helicopter; M_r—reactive moment of the main rotor; r—radius of the main rotor; ω—circumferential velocity; V—flight velocity of the helicopter; T_x—thrust of the tail rotor; L—arm of the tail rotor.

of the blade moving backward at this time is decreased by the same quantity, causing corresponding variations in aerodynamic forces and moments.

In solving the problem of the uniform aerodynamic loading of rotating

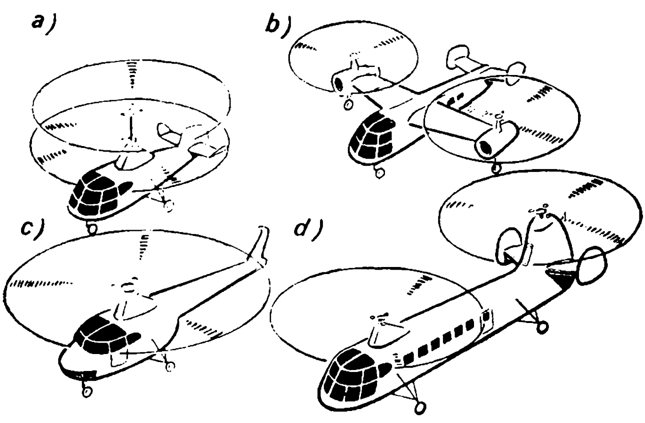


Fig. 20. Schemes of helicopters:

a—dual rotor with coaxial arrangement of main rotors; b—dual rotor with lateral arrangement of main rotors; c—single rotor with tail rotor; d—dual rotor with longitudinal arrangement of main rotors.

blades the designers invented a device called the "swashplate." It is a mechanism that automatically varies the angle of attack of a blade according to its rotation.

For a blade moving forward, i.e. having an increased relative velocity, the swashplate decreases the angle of attack; for a blade going backward, it correspondingly increases the angle of attack.

The swashplate is also structurally connected to the helicopter's control system. By moving the control stick forward, backward, to the right, or to the left the pilot can vary the angle of attack of the blades, as a result of which the cone described by the blades is inclined in the necessary direction.

Due to this the lift developed by the rotor forms a component in the desired direction and the helicopter begins to move in the path of the cone.

The fact that a blade moving forward receives an additional velocity while one going backward decreases its velocity relative to the air imposes definite physical limits on the flight speed attainable by a helicopter.

The maximum speed of a modern helicopter is only a little more than 300 kmph.

ROTARY-WING AIRCRAFT

How does one increase the maximum velocity of a flying vehicle with a main rotor? Obviously it is necessary to eliminate the main factors disturbing the increase of velocity, namely the existence of separation regimes. On the blade moving forward they arise due to the blade attaining critical velocity, while on the blade moving backward they are due to its critical angles of attack and, consequently, the separation of flow.

If the main rotor can be relieved (part of the lift removed from it) it then becomes possible to have smaller angles of attack throughout the path of the blade and hence an increase in the speed of flight.

This was the way the designers proceeded. They attached small lifting surfaces to the helicopter which develop lift during flight, thus partly relieving the main rotor.

There exist such designs in which, besides the surface (wing) whose lift relieves the main rotors in high-speed flight regimes, there are additional pulling propellers which also take part of the load during forward movement of the rotary wing aircraft.

SHORT AND VERTICAL TAKE-OFF AIRCRAFT

The take-off (mainly the take-off run) of an aircraft can be shortened by: increasing the aircraft's thrust-to-weight ratio, i.e. the ratio of engine thrust to the weight of the aircraft during take-off, by installing a more

powerful engine, by fitting an afterburner or launching boosters or by catapulting the aircraft; or by combining these methods.

On modern aircraft afterburner and launching boosters are used more often for increasing thrust during take-off. Today the problem of building vertical take-off aircraft has also been solved by using the inclination of thrust. A number of experimental aircraft have been built abroad. Some of them take off and land vertically while others start in the usual position but are provided with devices which turn the engine's gas jet and consequently the thrust (Fig. 21) through the necessary angle. Some are provided both with cruise engines, building thrust along the aircraft axis, and a couple of lift (booster) engines as well, creating vertical thrust (Fig. 22) during take-off. Sometimes the thrust of both cruise and lift engines is used.

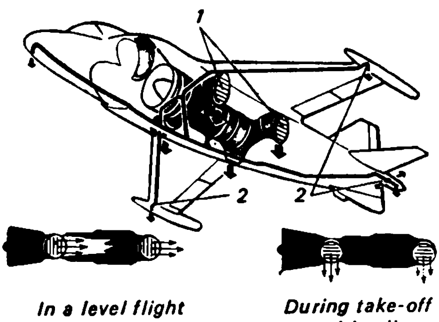


Fig. 21. Vertical take-off aircraft with swiveling nozzles:

1—swiveling jet nozzles; 2—control jets (During take-off and landing swiveling nozzles direct air from the fan and gases from the turbine downward; in normal flight nozzles are turned to rear, providing additional thrust).

Finally, there exist experimental aircraft abroad on which the wing together with the engines installed on it turn with respect to the fuselage, as a result of which a thrust inclination is achieved from 90° at take-off to 0 to 2° in level flight.

It is necessary to say here that all vertical take-off aircraft, irrespective of the way thrust inclination is achieved, must necessarily have a dual control system.

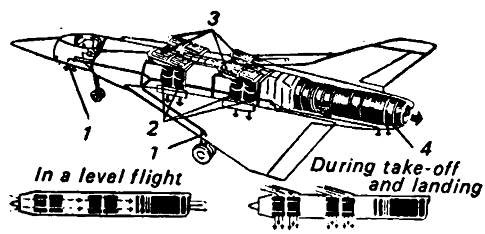


Fig. 22. Vertical take-off aircraft with lift engines:

1—control jets; 2—lift engines; 3—sliding air intakes; 4—cruise engine (aircraft has cruise engine to create horizontal thrust and a complex of separate engines which operate only during take-off and landing of the aircraft).

One is the usual one using the aerodynamic forces of the rudders during aircraft flight. The other is a special one intended for trimming and controlling the aircraft during the absence of aircraft speed, which functions until the moment the aerodynamic rudders become effective.

These are called control jets. When the aircraft's control stick or pedals are operated gas or compressed air flows out of the nozzles located on the wing tips or fuselage, creating a reactive force which gives rise to a corresponding rotating moment with respect to the aircraft axis, i.e. a force that turns the aircraft.

The great difficulty in building the vertical take-off aircraft is the necessity of installing additional engines, swiveling jets, etc. in such a way that in all possible positions during take-off and landing the vector of the thrust created by these devices passes through the aircraft's center of gravity. Soviet designers have successfully overcome these difficulties and have built a fighter aircraft capable of vertical take-off and landing.

AIRCRAFT WITH VARIABLE-GEOMETRY WING

First of all we will run over some of the points already discussed. Wings of low aspect ratio with a large sweep, including delta-shaped ones, differ from straight wings of medium and high aspect ratio from the aerodynamic point of view mainly due to the fact that for the former the magnitude of c_y grows with the increase of angle of attack at a considerably slower rate than for the latter.

As a result these wings attain the maximum value of c_y not at the angle of attack of 16–18°, as in the case of a straight wing, but at 30–35°. It is practically impossible to design an aircraft with wings havings an angle of attack of more than 15–16°. Therefore aircraft of low aspect ratio cannot make full use of the lifting properties of their wings during landing in spite of the application of various high-lift devices. Naturally the landing speed of such aircraft under identical wing loading conditions is considerably more than that of aircraft with straight wings.

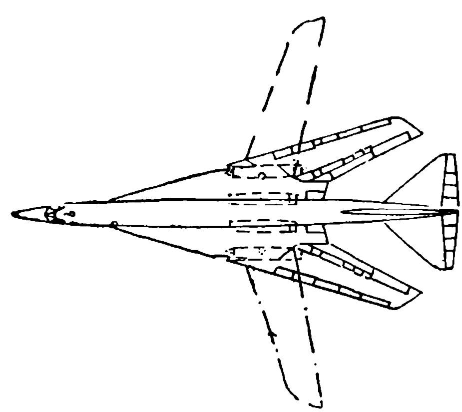


Fig. 23. Aircraft with variable-geometry wing: Boeing–733.

On an aircraft with a variable-geometry wing (Fig. 23) the angle of sweep can be regulated by turning the wing about the vertical hinge. In one extreme position the wing becomes a tapered one with an almost straight or nearly straight leading edge. In the other the sweep of the wing reaches its maximum. It thus becomes possible to use the aerodynamic

properties of the wing to the optimum, i.e. to achieve low landing speeds and a high value of aircraft lift-to-drag ratio at subsonic speeds besides a wing with large sweep back that assures the minimum drag at high supersonic speeds.

In addition it is necessary to solve a number of other aerodynamic problems connected with providing stability and control to the aircraft not only in extreme wing positions but also in transitional (intermediate) ones.

TAILLESS AIRCRAFT

The idea of building an aircraft without a tail originated quite a long time ago. It was considered advisable to do away with the tail and a large part of the fuselage by accommodating as much of the cargo and equipment as possible in the wing. By adopting the "flying wing" concept it is possible to have an aircraft with a high lift-to-drag ratio due to reduction in drag (c_x).

The realization of this idea was possible as long as the aircraft had low speeds and thick airfoils were used for the wing. Many experimental tailless aircraft of the flying wing type appeared. In the USA a bomber, the B–36, went into assembly line production.

The increase in flight speeds called for (necessitated) the use of wings too thin to accommodate anything. Again the fuselage appeared and the "flying wing" aircraft became simply an aircraft without a horizontal tailplane. Since the pitch control and trimming of the aircraft are carried out by elevons the wing loses a part of the lift in trimming, especially during landing. The angle of attack grows. The advantage of having no tail was negligible, even imaginary. Therefore the "flying wing" and tailless aircraft are not being developed today.

HYPERSONIC AIRCRAFT

Before talking about a hypersonic aircraft it is necessary to consider the whole range of flight speeds from low subsonic speeds to the orbital (circular) speed, i.e. the gamut from 0.2 M to 27.5 M. To date, according to foreign reports, aviation has mastered only one-ninth part of this range by achieving a speed of 3 M.

We will briefly review some basic facts from the material already considered. The air's resistance to aircraft motion is proportional to the area of the wing, the velocity head and the coefficient of drag c_x corresponding to the angle of attack necessary for flight at a given speed. On increasing the speed the quantity c_x varies in accordance with the aerodynamic characteristics of the aircraft while the velocity head increases parabolically (according to the square of the velocity). Therefore aircraft

drag grows by more than the square of the velocity.

c_x begins to increase when a local speed of sound has been attained on any part of the wing profile and continues to do so until the flow around the profile becomes wholly supersonic, after which c_x decreases but never to its initial value. Thus on the curve of c_x against the M number a 'crest' (Fig. 18) is observed in the range of transonic speeds which in its time was called the "sound barrier." The thinner the wing and the sharper and more arrow-like the leading edge the lower the crest.

In order to attain this or any other speed it is necessary to have a power plant capable of developing a thrust equal to (or exceeding) the resistance of the air to the aircraft motion at that speed. It follows from this that the given aircraft's aerodynamics and dimensions, the maximum flight speed and other flight data and qualities of the aircraft are determined by the absolute magnitude of thrust of the engine mounted on the aircraft (thrust-to-weight ratio) and the nature of thrust variation with speed and altitude.

If a curve of drag against the M number and a curve of engine characteristics (thrust versus M number) is plotted for one and the same altitude, i.e. the curves of necessary and available thrust are plotted to the same scale, then the point of intersection of these curves will show the maximum speed of the aircraft at the given altitude. The difference in the ordinates of the curves shows the excess thrust possessed by the engine at each speed.

On the magnitude of excess thrust depend the aircraft's "response," its ceiling and maneuverability.

The thrust of a propeller power plant, which consists of a piston engine and a propeller, decreases fairly fast with increasing flight speed and at a certain speed, depending mainly on the aerodynamic properties of the propeller, becomes zero. Due to this aircraft with a VMG could not attain a speed of more than 650 kmph. They occupy a small segment up to 0.5 M in the range of possible speeds.

During the period 1945–1950 the place of piston engines was taken by air-breathing engines: turboprop, turbojet and compressorless ramjet. In comparatively short order a turbojet engine achieved high subsonic speeds and also transonic speeds up to 1.2 M. The further development of the TRD, aerodynamics and aircraft construction made it possible to move further along the speed range up to 3 M.

How was this possible?

Air-breathing engines use air as the working substance and as an oxidizer of the fuel burned to heat the air. The thrust of a VRD is equal to the weight of air passing through the engine per second plus the quantity of fuel used for heating this air multiplied by the difference between the discharge velocity of the gas and the flight speed. Consequently to obtain

a large thrust it is necessary to throw back (to force through the engine) as large a mass of air as possible, to heat the air to the maximum temperature permitted by the engine design and to drive the exhaust gases from the engine nozzle at a velocity that exceeds the flight speed by as wide a margin as possible.

On increasing the flight speed the resultant increase in velocity head increases the quantity of air entering the engines and the "weight charge." Simultaneously the air is heated in the engine's intake system (diffuser). In order not to exceed the permissible temperature for the engine it is necessary to reduce the amount of fuel used to heat the air in the combustion chamber. The interaction of these contrasting processes mainly determines the nature of thrust variation with flight speed.

The thrust of a turbojet engine attains a minimum at a certain speed, increases with further increase of speed and reaches a maximum in the region of 2 M or more. The rate of thrust increase and the M number at which it peaks depends on the design peculiarities of the engine, mainly the degree of compression in the compressor, the permissible intra-turbine temperature and the perfection of regulation of the intake system (diffuser) and nozzle. After reaching a maximum the thrust begins to fall steeply with further increase in flight speed because the temperature of the air during retardation in the diffuser and compression in the compressor increases so much that the heat addition in the combustion chamber has to be reduced. This leads to a reduction in exhaust gas velocity. Additional burning of fuel after the turbine in a so-called afterburner increases the temperature of the gas and, consequently, the exhaust gas velocity. A TRD with a low pressure compressor and afterburner can achieve a large maximum thrust and can enter the zone of hypersonic speeds. The fact that the thrust of VRD increases with increasing velocity and the rate of increase approaches and can even exceed the rate of increase of aircraft drag is why VRD (TRD in particular) was able to take aviation to higher flight speeds and altitudes.

A further increase of speed, according to foreign reports, can be obtained with the help of the compressorless airbreathing engine, otherwise called the ramjet engine. The absence of a compressor and turbine permits the use of a large velocity head and high temperature in the combustion chamber. It is assumed that a ramjet engine with a supersonic airflow through the engine will enable us to achieve a speed of 10–12 M. However, engines in which the air is compressed solely due to the velocity head have no take-off (starting) thrust. Therefore their use is projected either in combination with power plants for starting and accelerating up to the velocity at which ramjet engines begin to be effective or in the form of combined (hybrid) engines that are currently being worked out. These engines structurally unite in one assembly engines of various types.

Air-breathing engines need air for the creation of thrust. Their use is possible only in the lower atmosphere, i.e. a limited altitude range where flying at high speeds involves the problem of heating of the vehicle.

A rocket engine creates thrust due to the flow through the nozzle of a mass consisting of the product of the combustion of the fuel with the oxidizer carried by the aircraft. The thrust of a rocket engine does not depend on the presence of atmosphere (flight altitude) and speed. It can equally well create thrust in a vacuum. In principle a rocket engine, ignoring the question of providing fuel during flight, can impart to an aircraft not only hypersonic but even cosmic velocities. Now we can pass directly to the hypersonic aircraft.

By a hypersonic aircraft is meant an aircraft that operates independently without any complicated launching devices, takes off by itself and lands on standard runways, can develop maximum speed in the range from 5 M and up and can be controlled in the whole range of flight speeds and altitudes.

From the above the conclusion can be drawn that among existing types of engines the following hybrid engines are suitable for aircraft of low hypersonic speed: combined air-breathing jet engines (turbo-prop plus ramjet, Fig. 24) and combined air-breathing and rocket engines (turbo-prop plus rocket); and for flight in the whole range of hypersonic speeds combined air-breathing and rocket engines and pure rocket engines.

The possibility of obtaining the thrust necessary for flight is only one of the problems to be solved in creating a hypersonic aircraft. The second and maybe main problem is that of providing an acceptable ratio of weight of engine and fuel to weight of aircraft and an acceptable weight of aircraft as a whole. Here the specific weight of the engine and its specific thrust and consumption play a significant role.

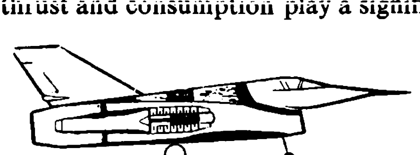


Fig. 24. Aircraft with a combined engine.

Fuel requirements break down into the fuel necessary for take-off, climbing to the required altitude, accelerating to the required speed, cruising flight and maneuvering during descent and landing. The major component is the fuel required for climbing and acceleration. Naturally the higher the speed the aircraft is to be accelerated to the more work is demanded and, consequently, fuel.

Thus to obtain a speed equal to 1 M it is necessary to spend 4,400 kg·m of work per kilogram weight of aircraft, for a speed of 10 M—100 times more, for a speed of 20 M—400 times more.

Calculations for a hypersonic aircraft with a rocket engine show that with the available modern chemical fuels so much is needed to accelerate the aircraft to high hypersonic speeds that it is practically impossible to

accommodate it aboard the aircraft.

It is no chance that the hypersonic aircraft with a liquid propellant rocket (ZhRD) X-15 being tested in the USA—which has reached a speed of 6.6 M—starts not from the ground but from a mother aircraft as an altitude of about 12,000 m.

The third problem is to work out aerodynamic shapes for the aircraft that will guarantee, from the point of view of energy loss, controllable and economic aircraft flight over a whole speed range covering hyper, super and subsonic speeds.

The aerodynamics of subsonic speeds differs widely from the aerodynamics of supersonic speeds because at supersonic speeds the air behaves as a compressible medium. The aerodynamics of hypersonic speeds, in turn, differs from the classical aero-thermodynamics (subsonic) and gas dynamics (supersonic) by the fact that the air is no longer considered to be a continuous medium.

At the high altitudes where a hypersonic aircraft develops its maximum speed the air is so rarefied that the length of the mean free path of molecules becomes measurable against the dimensions of the aircraft, such that a separate particle of air meets the aircraft, only once. This aerodynamics considers the effect of the interaction of air with a body not as the result of a redistribution of pressure in a continuous airstream surrounding the body but as the combined result of the collisions of separate air particles with the moving body, taking into account the centrifugal forces exerted on the particles when their path is bent as they move along the curvilinear surface of the body.

In analyzing the forces acting on the moving body the aerodynamics of hypersonic speeds also takes into account that the collision of air particles with the body generates high temperatures which brings about processes of molecular disintegration, dissociation and ionization of molecules and the formation of plasma. Plasma is gas atoms that have lost some of their electrons and have been converted into charged atoms known as ions. In other words, plasma is a mixture of electrons and ions. The stream of charged, ionized particles in the vicinity of the flying body generates electrical currents and an electro-magnetic field. Thus at high hypersonic speeds an aircraft will be flying surrounded by a layer of plasma.

Theory shows that the best shape for a hypersonic airfoil is a triangular wedge with a flat lower surface of a maximum relative thickness of about 5% located at a distance of two-thirds of the chord from the leading edge.

For a supersonic aircraft the best form of airfoil is an almost symmetrical thin profile (relative thickness 3–5%) formed by the arcs of a circle, while for subsonic aircraft it is a concave one with a relative thickness of 9–12%. From this it can be appreciated how difficult it is to work out the aerodynamic shape of a wing that would satisfy the requirements of all

three speed ranges.

It also has to be remembered that at hypersonic speeds it is possible and even necessary to take into account the aircraft's "release" from its own weight due to the centrifugal force arising during flight at constant altitude above the surface of earth. The appearance of centrifugal force is explained by the fact that since the earth is a sphere the trajectory of flight is essentially a curvilinear (circular) one and during any curvilinear motion, as is known, centrifugal force appears. However, this "release" becomes significant only during flight at speeds exceeding 10 M. At 10 M nearly 15% of the weight is "lost," at 20 M nearly 50% and at 27.5 M, i.e. orbital velocity, 100%, resulting in weight lessness.

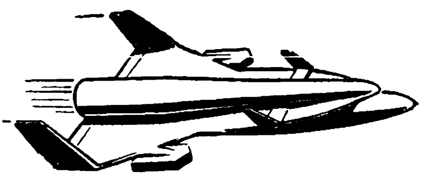


Fig. 25. Air-breathing cosmic aircraft.

In reaching a speed equal to orbital velocity or more, a hypersonic aircraft becomes a new type of jet flight vehicle, an air-breathing cosmic aircraft (Fig. 25).

This piloted flight vehicle with supporting surface (in particular the winged one) is intended for flight in the atmosphere and cosmic space. It has the properties of both aircraft and spaceship; repeated use, ability to take off from a runway, to accelerate to orbital speed, to perform flight in cosmic space and to return to earth and land on a runway. One of the projected uses of such aircraft is space transport, including provisioning of manned orbital station and relief of crew.

The power plant for such an aircraft will probably be a combination of air-breathing jet engines for flight within the limits of the atmosphere and liquid propellant rocket engine for flight in cosmic space. The possibility of using nuclear engines is also being studied.

Currently research on the many complicated problems involved in creating such an aircraft is being conducted abroad. Scientists and designers are attacking hypersonic speeds from both sides. On the lower boundary of this region they are advancing research on supersonic speeds with the help of powerful supersonic wind tunnels. After these preliminary steps the findings are consolidated and widened with full-scale flight tests of an experimental aircraft. On the upper boundary of hypersonic speeds scientists and rocket-designers, creators of cosmic engineering who have successfully investigated the earth's "environment," are advancing toward space. They are studying the problem of creating a spaceship in the form of an orbital aircraft, i.e. a hypersonic aircraft with speed equal to orbital velocity which is the last step in the rocket system. After taking off and going into orbit such an aircraft can return to the dense layers of the

atmosphere, maneuver using its aerodynamic ability on the descent trajectory and land in a designated region.

Work is also in progress to create a system for the launching of orbital aircraft consisting of a number of aircraft joined together. These will disengage from one another in a consecutive order with the orbital aircraft launching from the last of them. The main aim of this research, according to foreign reports, is to achieve multiple use for all stages of the system and also to improve the launching conditions of the last stage, i.e. the spaceship proper.

The difficulties obstructing the creation of an automatic hypersonic aircraft are thus clear. However, there is no doubt that the mighty intellect of man will find a way to solve this most difficult problem.

SECTION THREE

Aircraft Engines

AIRCRAFT ENGINE. GENERAL

Engines and propeller

A machine (technical device) for the conversion of chemical nuclear, solar, thermal, electrical or any other form of energy into mechanical energy is called an engine. In other words, an engine generates mechanical energy.

According to the form of energy converted they are classified as chemical, nuclear, solar, thermal or electrical engines.

According to their purpose engines are classified as stationary or mobile. The former functions on the stationary foundation of an energy (power) plant, for example at power stations, in factories and plants. The latter are installed in transportation devices, for example flying machines, automobiles, tractors, river and sea vessels which serve in the air, in outer space, on the earth, on water and under water.

Mobile engines, in their turn, are divided according to their application, as engines for spaceships (which are sometimes called space engines) aircraft engines, automobile engines, marine engines, diesel locomotive engines and others.

The mechanical energy that is generated by a mobile engine is used to cause movement of the vehicle in which it is installed.

A device that uses the energy transmitted to it by the engine to create a propulsive force to move a transportation device is called a propeller.

On some flying machines a propeller using the energy that is transmitted to it by the engine is used, while on others the motor and the propeller are integral parts of the engine.

The engines of flying machines (aircraft and space engines) differ not

only in the form of energy transformed in the engine into mechanical energy but also in many other features: working cycle, design criteria, fuel used, method of creating propulsive force, i.e. thrust, dependence (or independence) or working body on the surrounding medium, law of thrust (power) variation of aircraft engine with flight altitude and so on.

It will be recalled that the substance used to carry out the working cycle is called the working substance of a heat engine. Air, a mixture of air and fuel and the products of combustion of this mixture are used as the working substance for aircraft engines.

Almost all the engines used to date and those now used in aviation and astronautics are heat engines, i.e. machines using heat given out during the combustion of fuel or some other process for conversion into mechanical energy.

According to the means of creating thrust engines are divided into engines with propeller thrust, those with jet thrust, usually called jet engines, and engines with combined thrust.

The first create thrust with the help of an airscrew (propeller) and the second by combining in themselves the engine and propeller. The third create part of their thrust themselves and another part with the help of a propeller.

In modern aviation jet engines and engines with combined thrust are mainly used; only jet engines are used in rocket techniques and astronautics.

As regards the dependence (or independence) of the working body on the surrounding medium, the engines of flying machines are divided into two basic classes; engines using atmospheric air as the working body or as a source to form it and engines whose working body does not depend on the surrounding medium. Almost all aircraft engines belong to the first category while those used in rocketry and astronautics belong to the second. Jet engines belonging to the first category are called air-breathing jet engines while those belonging to the second category are called rocket engines.

Aircraft engines, according to their constructional features, are divided into piston engines, which were widely used in the first half of this century, and gas turbine engines which are the basic engines of modern aviation.

These types of engines also differ in the working cycle they use.

Requirements of an aircraft engine

An aircraft engine must satisfy the following requirements: it must start easily on the ground and in flight, must operate steadily in a wide range of regimes (from the maximum to the minimum) on the ground and in flight, developing the required power (thrust), must have high reliability and a long service period. In addition it must be light, economical and

relatively small, as also easy to control and simple to maintain.

The flight specifications of an aircraft are to a large extent determined by the ratio of the total power (thrust) developed by the engines under static ground conditions to the weight of the aircraft and also by the dynamic and high-altitude characteristics of the engines. These characteristics show how the power (thrust) of the engine and its fuel consumption vary on varying the speed and altitude of flight.

Weight of the engine. The small weight of an aircraft engine is one of the most important features distinguishing it not only from stationary but also from many mobile engines, for example marine engines.

The weight of engine necessary for a unit of the power (thrust) it develops is called the specific weight. The less the specific weight of an engine the lighter the engine.

For an aircraft to achieve uniform, level flight with some speed at a certain altitude it is necessary that the specific weight of the engines relative to their thrust at these flight speeds and altitudes be less than the lift-to-drag ratio of the aircraft by as many times as the total weight of the engines is less than the weight of the aircraft.

From this it follows that the less the specific weight of the engine the better the performance under identical conditions that can be obtained from the aircraft on which it is installed.

Let us assume that the specific weight of the engine at a given flight speed and altitude is equal to the lift-to-drag ratio of the aircraft. Then the total weight of the engines must be equal to the total weight of the aircraft.

This, however, cannot be, because the total weight of the aircraft consists of the weight of its body, the weight of the power plant, which includes the engine, and the weight of the total load including the payload and the fuel for engine operation. Therefore this specific weight of an engine would make flight at a given speed at a given altitude impracticable.

Let us examine the effect of gradually decreasing the specific weight of the engine at a given flight speed and altitude. In doing this we will first arrive at a specific weight (considerably less than the lift-to-drag ratio of the aircraft) where the aircraft will be able to perform level flight at the given speed and given altitude. But this flight would be of very short duration and the payload would be very small.

A further decrease in the specific weight of the engine will enable the aircraft not only to perform level flight at the given speed and given altitude but also to increase the range of this flight and the payload.

A small engine weight is also the key to the aircraft's required take-off properties and rate-of-climb.

Engines intended to create vertical thrust on vertical take-off and landing aircraft must be particularly light ones.

Effectiveness of the engine. One of the most important properties of the aircraft engine is its measure of efficiency or the specific fuel consumption, called its efficiency. The greater the efficiency of the engine and correspondingly the lower the specific fuel consumption, the higher the engine's effectiveness.

Specific fuel consumption is the consumption of fuel per unit power (thrust) developed by the engine.

The efficiency of the engine is very important for all aircraft but especially for long-range aircraft.

To compare two engines developing identical power and having one and the same specific weight but different efficiency: the more efficient engine will provide the aircraft with either longer duration and range of flight for a given payload or greater payload for the same duration and range of flight.

In either case the more efficient engine will make the use of the aircraft more efficient. Evaluation of the efficiency of using an aircraft as a transport machine is carried out with the help of a quantity equal to the product of the weight of the payload of the aircraft and its flight range. The larger this quantity the higher the aircraft's efficiency as a transport machine.

In both cases the more efficient engine reduces fuel consumption and lubricating materials per unit payload carried over a unit distance (usually this consumption is measured in kilograms per ton–kilometer), and consequently the operational cost of the aircraft per ton–kilometer of transportable payload.

Size of the engine. One of the fundamental requirements to be satisfied by an aircraft engine is small size. The overall size of an engine is its maximum dimensions lengthwise, widthwise and heightwise.

The overall dimensions of the engine as determinants of frontal area are very important for the aircraft.

The area of the projection of the overall contour of the engine on a plane perpendicular to engine axis is called its frontal area. The frontal area per unit power (thrust) developed is called the specific frontal area of the engine.

The quantity converse to the specific frontal area, representing the power (thrust) of the engine per unit of its frontal area, is called the specific frontal (thrust) power.

The aerodynamic resistance of the aircraft's power plant depends on the magnitude of the engine's specific frontal power. The larger its magnitude the lower the aerodynamic resistance.

Engines of the earliest aircraft

Working in the seventies and the beginning of the eighties of the last

century on creation of his new aircraft, A.F. Mozhaiskii had to solve a highly complicated problem regarding the power plant.

Gas turbine engines did not exist and the reciprocating internal combustion engine that had appeared a little earlier had not reached the perfection necessary for use as an aircraft power plant. These engines were very heavy and bulky.

A.F. Mozhaiskii's aircraft therefore had a steam power plant. It consisted of two reciprocating engines identical in construction but having different power outputs, boilers and condensers. The power of the whole plant was 30 hp.

The steam engines of the power assembly of A.F. Mozhaiskii's aircraft were twin-cylinder, double-expansion steam engines. The larger engine developed a power of 20 hp at 300 rpm and weighed 47.6 kg; the smaller one developed 10 hp at 450 rpm and weighed 28.6 kg. Total weight of the engine and boiler is 140.6 kg. The specific weight of the power plant was nearly 4.7 kg/hp. This small specific weight for a steam power plant was undoubtedly a remarkable achievement of engineering for the time and testified to A.F. Mozhaiskii's great design talent.

Besides A.F. Mozhaiskii's aircraft steam engines were installed on other flying vehicles, particularly on the French aircraft of K. André (1897).

RECIPROCATING INTERNAL COMBUSTION ENGINE

Birth of the aircraft reciprocating internal combustion engine

The overwhelming majority of aircraft reciprocating engines used to date, and those still used, are internal combustion engines with forced ignition, working on a four-stroke cycle with constant volume combustion. The first internal combustion engine working on this cycle was built in 1876 (Fig. 26). It was a stationary engine, worked on a gaseous fuel (lighting gas) and was low-speed, i.e. developed a small number of rotations per unit time.

Its efficiency, however, was much higher than that of the steam engine of those days. It had the same power output as engines of today in spite of the development they have undergone over more than a century.

In the cylinder *6* a piston *7* reciprocates upward and downward. The piston is connected to the crankshaft *9* by a connecting rod *8*.

In the time the piston completes two strokes in the cylinder (one from the top down and other from the bottom up) the shaft makes one rotation.

In the upper part of the cylinder two valves are fitted: inlet valve *4* and exhaust valve *2*.

The working cycle of the engine is as follows: during the downward movement of the piston a mixture of air and lighting gas enters through the open inlet valve inside the cylinder via the manifold *5*, after which the

piston compresses the mixture by moving upward. When the piston reaches its topmost position (top dead center) the mixture is ignited with the help of a special igniter *3* and burns very rapidly.

The products of combustion formed exert a force on the piston. This force is transmitted through the connecting rod to the crank-shaft and is used to do other useful work. During the downward movement of the piston the products of combustion expand and during its subsequent upward motion they are pushed out of the cylinder through the open exhaust valve via a manifold *1*. Thus the cylinder is cleaned ready for a new charge of the mixture of air and lighting gas.

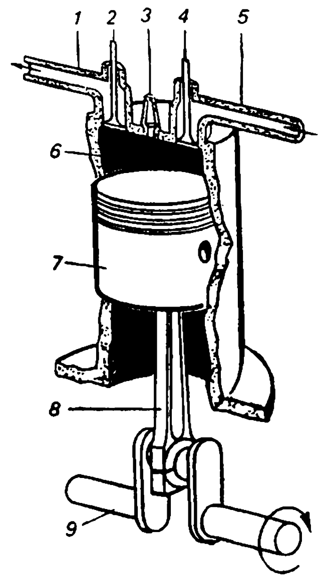


Fig. 26. The working of the four-stroke internal combustion engine.

The working scheme of a gas engine shown in Fig. 26 laid the foundation of much higher-speed and hence (on the basis of specific weights) lighter four-stroke engines built a few years later. These no longer worked on gaseous but on liquid fuel—gasoline.

The first four-stroke gasoline engines had one or two cylinders and developed a modest power (about 3–5 hp), clearly inadequate for successful application to aircraft. Subsequent development of these engines accompanied by increases in power and speed and a decrease in specific weight made their use in aviation not only possible but also expedient.

The first aircraft with reciprocating internal combustion engines appeared at the beginning of this century (1903–1909). The engines of these aircraft had from three to eight cylinders and developed power ranging from 20–30 to 60–80 hp. Their specific weight was from 1.5 to 4 kg/hp.

The subsequent development of aircraft reciprocating internal combustion engines, usually simply called reciprocating aircraft engines, proceeded in the following fundamental directions; increase in power; maintaining the power that can be developed under ground conditions after climbing to some altitude; reduction in specific weight; increase in efficiency, specific frontal power, reliability and service life; simplicity, and later on automation of engine control on the ground and in flight.

Radial and in-line engines. Air and liquid cooling

According to the structural shape, determined by the location of the

engine cylinders with respect to each other and the crankshaft, reciprocating aircraft engines are classified into radial and in-line engines.

A radial engine is a reciprocating aircraft engine with radially located cylinders whose axes lie in one, two or more planes perpendicular to the axis of the crankshaft.

In each plane normally five, seven or nine cylinders are located.

The in-line engine is a reciprocating aircraft engine with one, two or more rows of cylinders whose axes are parallel in each row and lie in a plane passing through the axis of the crankshaft. Usually four or six cylinders are located in each row.

Reciprocating aircraft engines are also classified according to the method of cooling the cylinders.

In the case of an air-cooled engine the extraction of heat from the cylinders is carried out by the air blowing round them. In the case of a liquid-cooled engine it is done by circulation of a liquid.

One of the basic elements in a liquid cooling system is the radiator. It is a heat-exchanger through which the liquid that has cooled the cylinders flows. The liquid which was heated by the heat extracted from cylinders gives this heat in turn to the air cooling the radiator.

Air and liquid-cooled reciprocating engines were the basic engines of aviation for the first half of this century. The reciprocating engines now used in aviation have a simpler and more convenient air cooling operation.

Carburetion

The process of making a combustible mixture with the purpose of preparing the fuel to be burned in the engine is called carburetion.

External carburetion is the process of making the combustible mixture wholly or mainly outside the engine cylinders. Internal carburetion is where this process is carried out wholly inside the cylinders. Both processes are used in reciprocating aircraft engines.

External carburetion is usually performed by a carburetor. A carburetor is a device designed to prepare a combustible mixture (from a light liquid fuel and air) of the required composition in accordance with the weight rate of airflow, i.e. with the weight of air passing through the carburetor per unit time and then entering the engine cylinders.

Internal carburetion is brought about by direct injection of fuel, i.e. by delivery of fuel by means of a pump and a nozzle directly into the engine cylinder at the time of the suction stroke.

Valve timing and ignition

The periodic operation of the inlet and exhaust members (valves or ports) of a reciprocating internal combustion engine, filling the engine cylinders with a fresh charge of combustible mixture and extracting from

them the products of combustion, is called the valve timing. The moments of opening and closing of inlet and exhaust members are called valve phases.

For every type of engine the most advantageous valve phases, ensuring maximum possible power and minimum specific fuel consumption under steady operational conditions of the aircraft engine, are selected on the basis of tests.

The distribution of gas (valve timing) is performed by a special mechanism called the valve gear.

In reciprocating aircraft engines burning light fuel, electrical (spark) ignition of the combustible mixture is used. The most advantageous moment to create the spark between the electrodes of the spark plug for every type of engine is chosen experimentally.

Propeller reduction gear

The mechanism to reduce the rotational speed (number of rotations) of the propeller shaft with respect to that of the engine shaft is called the propeller reduction gear (or simply reduction gear).

In reciprocating aircraft engines it is very important to have the maximum possible number of revolutions of the crankshaft in the maximum regime of engine operation because this allows the maximum possible engine power to be obtained (under the given conditions). However, in the majority of cases this number of revolutions of the crankshaft does not coincide with the number of revolutions of the propeller shaft at which the maximum efficiency of the propeller is obtained.

Therefore, even though the propeller reduction gear adds weight to the engine and involves the expenditure of part of the power developed by the latter, in many cases it appears to be beneficial to provide the engine with a reduction gear with a gear ratio such that maximum or near-maximum propeller efficiency is obtained.

The ratio of the number of propeller shaft revolutions to the number of revolutions of the engine crankshaft is called the gear ratio. It is always less than unity.

The first altitude engines

The flight altitude of aircraft at the beginning of this century was very modest. The record altitude set in the year 1909 just exceeded 150 m.

The rapid increase in flight altitude that began int he following years placed specific "altitude" requirements on aircraft engines. A carburetor that prepared a combustible mixture of the required composition under ground conditions did not maintain this desired composition after climbing to an altitude.

It seemed necessary to introduce in the construction of carburetors a special device to maintain the necessary composition of the combustible

mixture with varying flight altitudes. This is known as an altitude corrector. Later on correctors became an essential element of all aircraft carburetors.

However, the presence of a carburetor with altitude corrector cannot prevent a natural decrease of engine power after climbing to considerable altitudes. With increasing altitude the pressure and density of the atmospheric air which is the main source of the working body in the engine decreases. The power developed by an engine on the ground decreases at an altitude of 3,000 m by approximately 30% and at 5,500 m by twice as much. Further climbing naturally brings about a still steeper decrease in engine power.

Scientists and builders of aircraft engines in different countries began to consider the problem as to what should be done so that the power of the aircraft engine did not decrease with altitude. As a result of intensive work reciprocating engines were produced whose power (the pressure of air or combustible mixture in the inlet manifold) did not decrease up to a certain altitude called the engine altitude, the critical altitude or the design altitude of the engine. The altitude engines were divided into two classes: without supercharger and with supercharger.

The density of air or combustible mixture at the entrance to the cylinder in the case of the first type of engines remained almost the same, from the ground to the design altitude close to the density of the atmospheric air at the design altitude. Because of this the engine developed the same power from the ground to the design altitude, operating with fully opened throttle at the design altitude and with partly closed throttle on the ground and at altitudes below the design altitude. Such engines were frequently termed oversized engines because the working volume necessary to obtain there quired power at the design altitude was more than the working volume necessary to obtain the same power on the ground with full throttle opening.

Altitude engines without supercharger had a design altitude of 2,000-3,000 meters. They were widely used in aviation in the twenties and the first half of the thirties. However, by this time they were being replaced by more perfect altitude engines with a supercharger which began to be introduced in aviation around the beginning of the thirties.

Altitude engines with supercharger

Increasing the weight of fresh charge entering the cylinders of an engine by comparison with the weight of the charge that would have entered the cylinders of the same engine during simple suction from the atmosphere is termed supercharging. Supercharging is accomplished by increasing the manifold pressure (and due to this also the density of air or combustible mixture) in the inlet manifold with the help of a special compressor.

Let us recall that a compressor is a device for compressing air, some other gas or gaseous mixture. The compressor used to compress the air or combustible mixture before entering the cylinders of a reciprocating internal combustion engine is called a supercharger.

In the case of altitude engines with a supercharger the same pressure of air or combustible mixture is maintained at the entrance to the cylinder from the ground to the design altitude. Due to this any decrease of engine power is prevented (or at least is greatly slowed down) up to the design altitude or even slightly beyond. In the first such engines this pressure was close to the atmospheric pressure of the air on the surface of the earth. Thus the supercharger was used only to ensure the necessary critical altitude.

Later on, however, the supercharger began to find application as a highly effective means of increasing engine power on the ground. This dual application of the supercharger substantially increased the engine power on the ground without involving an increase in its working volume and maintained this raised power up to the required altitude.

While using the supercharger in this way the same pressure of air or combustible mixture at the entrance to the cylinder is maintained up to the design altitude but in magnitude it considerably exceeds the atmospheric pressure on the surface of the earth.

A supercharger (usually centrifugal) is driven by the engine crankshaft or by a gas turbine using the energy of the exhaust gases. In the latter case the supercharging is carried out with the help of a special unit called the turbo-supercharger, which consists of a compressor and a turbine developing the power necessary to drive it.

According to the number of stages the centrifugal superchargers are classified into single and two-stage (Fig. 27).

Many engines with turbo-superchargers also had a centrifugal supercharger with a small design altitude driven by the engine crankshaft.

This two-stage system of supercharging, termed combined supercharging, ensured an engine altitude of about 8,000–10,000 m and more.

In flight supercharging can be effected (both for engines with superchargers and for those without) directly with the kinetic energy of the airstream. For this purpose the air intake is installed with the inlet port facing the free airstream. The supercharging accomplished in this way is termed ramming. The engine design altitude obtained from ramming depends on the flight speed: at low speeds it is insignificant, rapidly increasing with increasing speed.

Reciprocating engines with superchargers were the principal aircraft engines in the pre-war years and at the time of the Second World War.

A.D. Shvetsov, V.Y. Slimov, A.A. Mikulin, S.K. Tumanskii and others were the main designers of the Soviet altitude reciprocating engines.

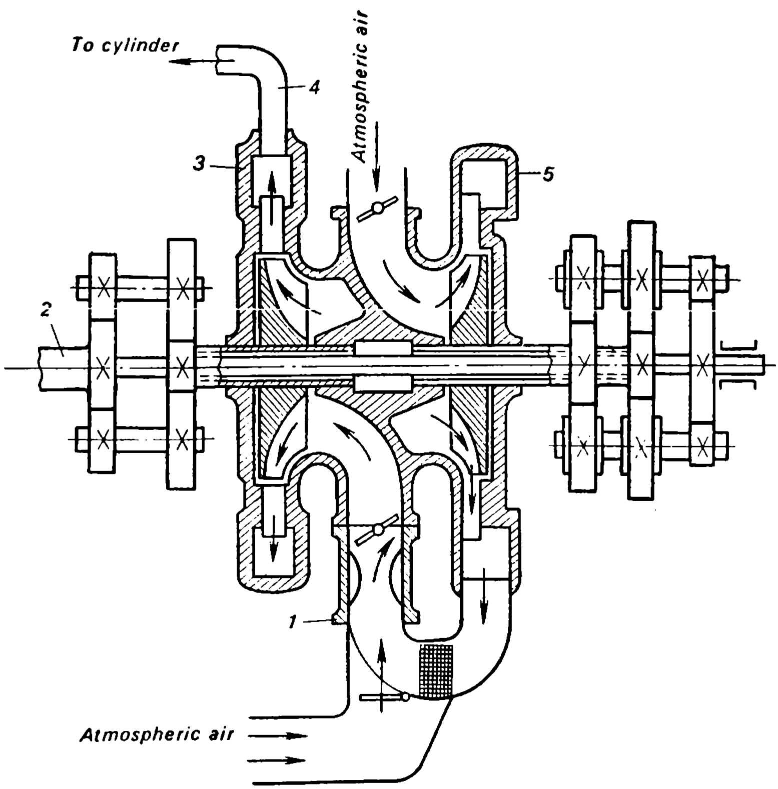


Fig. 27. Two-stage centrifugal supercharger:

1—carburetor; 2—crankshaft; 3—second stage of the supercharger; 4—engine inlet manifold; 5—first stage of the supercharger.

GAS TURBINE IN AVIATION

Toward the end of the first half of this century the power of altitude reciprocating engines had reached 3,500 hp and more. The number of cylinders had reached 24 in the case of in-line engines and 28 in the case of radial ones. The specific weight had been reduced to 0.4–0.6 kg/hp while the specific frontal power had been increased to 1,500–2,500 hp/m^2.

Combined turbo-piston engines were produced with higher efficiency than that of conventional piston engines. The specific fuel consumption of these engines was about 170–180 gal/hp·hr. This is about 20–25% less than for the usual reciprocating aircraft engines of that time and almost 1.5 times less than that for the gasoline engines of modern automobiles.

The greater efficiency of the turbo-piston engine is explained by the fact that it combines a reciprocating internal combustion engine and one or more gas turbines. The turbine uses the energy of the exhaust gases of the

reciprocating engine and gives its power to the engine crankshaft, assisting it further in turning the propeller. The energy of the gases leaving the turbine can be used to create additional (reactive) thrust.

After the war began gas turbine engines were widely adopted first in military and later on in civil aviation.

The changeover from the reciprocating engine to the gas turbine engine in aviation is explained by the fact that increasing flight speeds, especially those approaching the speed of sound, demanded a steep increase in the output of the power plant. A power plant in the form of a reciprocating engine could not provide the necessary useful (thrust) power with allowable dimensions and weight of power plant. Unlike a reciprocating engine, a gas turbine engine of comparatively small dimensions and weight provides a large amount of power in flight.

The reciprocating aircraft engine ASh-82FN, weighing 900 kg, has a maximum power of 1,850 hp at the propeller shaft. The thrust power in flight corresponding to it does not exceed 1,500 hp. The gas turbine aircraft engine Vk–1, weighing about the same, develops a thrust power of up to 10,000 hp at a flight speed of 1,000 km/hr.

Compared with a reciprocating engine, a gas turbine engine usually possesses better speed characteristics. The thrust power of a gas turbine engine over a wide range of flight speeds continuously increases with increasing speed. The thrust power of a reciprocating engine, however, increases with increasing speed at low flight speeds, varies little at medium subsonic speeds, but decreases at transonic speeds due to the fall in propeller efficiency.

General information about blade machines and turbines

The gas turbine belongs to the class of blade machines, i.e. machines whose basic working elements are blades (vanes). These machines are subdivided into two fundamental groups, machines delivering energy to a flow of liquid, steam or gas passing through them and machines extracting energy from them.

The work of the great Russian scientist N.E. Zhukovskii on the vortex theory of propellers and axial fans is the basis of the modern theory of blade machines.

A blade machine in which the energy of a working body flowing through it is converted into mechanical work at the machine shaft with the help of a rotor fitted with blades is called a turbine.

A turbine is called a hydraulic turbine if its working body is liquid; a steam turbine if steam serves as the working body; and a gas turbine if gas is used as the working body.

The gas entering a turbine having higher pressure and temperature in comparison with the atmosphere possesses potential energy. While passing

through the turbine the gas expands, considerably increasing its velocity and kinetic energy on account of the corresponding reduction in potential energy. A large part of the kinetic energy of the gas is used in creating the force effect on the blades that sets the turbine rotor in motion.

The first steam turbines suitable for use in energetics were built at the end of last century. Before the creation and introduction of the gas turbine engine in aviation efforts were made to use steam turbines on aircraft. However, this was not found practical due to the steam boiler and the large size of the condenser.

The idea of a gas turbine came up a few centuries ago. Professor V.M. Makovskii, one of the pioneers of Soviet gas turbine construction, in his exhaustive work *Experimental Investigation of Internal Combustion Turbines with Constant-pressure Combustion,* which was written about half a century ago, considered the "smoke machine" in Leonardo da Vinci's album to have been the prototype of a gas turbine. It is a spiral wheel set in motion by the gases emerging from a cell and was to be used to rotate a barbecue spit over the fire. Of course, from this prototype to a real gas turbine was a long step.

One of the first inventors to build a metallic gas turbine was a Russian engineer, P.D. Kuzminskii. In the period from 1887 to 1900 P.D. Kuzminskii designed and built a gas turbine unit consisting of an air compressor, a combustion chamber (steam and gas generator) and a multi-stage turbine of original design. This unit was designed for a small motor launch.

Principle of working of a gas turbine.
Impulse and reaction turbine

A gas turbine converts a part of the potential energy of the gas first into kinetic energy and then into mechanical work at the turbine shaft. In the nozzle blades of the turbine the gas is expanded and acquires a substantially high velocity. Then while flowing through the channels between the rotor blades it gives away part of its energy to the rotor, which is thus set in motion and does the mechanical work.

In a great many gas turbines the gas is expanded not only in the nozzle blades but also in the channels between the rotor blades. Such turbines are termed reaction turbines in contrast to impulse ones in which the gas is expanded only in the nozzle blades.

Depending on the direction of flow of the gas stream through the turbine with respect to its axis turbines are classified as axial or radial. In the first type the flow of gas is parallel to the axis of the turbine. In the second it is mainly in a direction perpendicular to the axis of the turbine.

In aviation mainly axial gas turbines are used because at high power they have roughly the same efficiency as radial ones but they weigh much

less. Therefore further discussion will be mainly confined to axial gas turbines. The shaft of the turbine *1* (Fig. 28) is connected by some method or other with the disc *2* carrying rotor blades *3* on the rim. The nozzles *4* are fixed in the casing *5*.

The disc with the rotating blades located on the rim is called a rotor. The shaft together with the rotor forms the rotor of a single-stage turbine.

In the impulse turbine the expansion of gas from the initial pressure p_0 to the final pressure (pressure at the exit of the turbine) p_2 takes place in the nozzle *4*. It is accompanied by a decrease in temperature. In the nozzles there is a drop in heat which is converted into the kinetic energy of the gas jet. During the process of expansion the velocity of the gas increases from c_0 before the nozzles to c_1 afterward.

After leaving the nozzles the gas enters the channels between the rotor blades where its velocity is reduced from c_1 to c_2 and its kinetic energy decreases accordingly. While passing between the rotor blades the gas leaves a considerable part of its kinetic energy there. It is this part of the energy of the gas that is used to perform mechanical work on the turbine shaft.

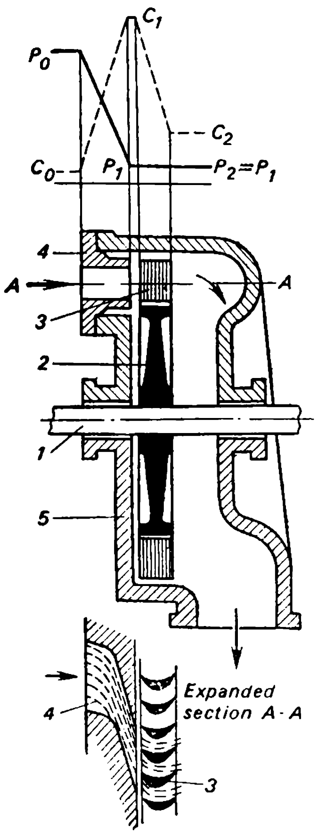


Fig. 28. A single-stage impulse turbine:

p—pressure of the gas; c—velocity of the gas.

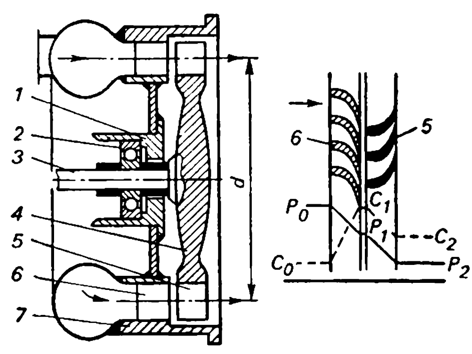


Fig. 29. A single-stage reaction turbine.

During the flow of gas around the rotor blades, as in the case of flow of air around an aircraft wing, a difference of pressure is formed between the two sides of the rotor blade. The difference causes the gas flow to exert a force on the rotor blades. This produces a turning moment that rotates the turbine rotor.

The simplest reaction turbine is shown in Fig. 29. A shaft *3* is supported in the bearings *2*, one of which, situated in the casing *1*, is shown in the figure. The disc *4* carries rotor blades *5* on the rim. Stationary nozzle blades *6* are fixed in the casing *7*.

The gas enters the nozzles (the channels between the nozzle blades) and is expanded there from the initial pressure p_0 to a pressure p_1 which is more than the pressure p_2 at the turbine exit. During the process of expansion the velocity of the gas increases from the initial value c_0 before the nozzles to c_1 afterward.

After leaving the nozzles the gas enters the channels between the rotor blades and is there expanded in them from pressure p_1 to pressure p_2. During this the velocity of gas relative to the rotating blades increases while the velocity relative to the stationary elements of the turbine decreases from c_1 after the nozzles to c_2 at the exit of the channels between the rotor blades.

So that the gas can be expanded in the channels between the rotor blades they are made to coverage in the direction of the gas flow.

The mechanical work on the shaft of a reaction turbine is produced not only by the kinetic energy of the gas entering the rotor but also by the drop in the enthalpy of the gas during expansion in the rotor (in the channels between the rotor blades). It may be recalled that enthalpy is a parameter of the state of a gas determined by the quantity of heat that is necessary to heat 1 kg of gas constant pressure from absolute zero or from 0°C to the temperature of the gas.

The difference in the enthalpy of the gas at the beginning and at the end of its expansion is called the thermal drop, heat drop or drop of heat.

Turbines or stages with different degrees of reaction are distinguished according to the distribution of the thermal drop in the turbine or its stages (between the nozzle blades and the rotor blades).

A quantity showing what part of the heat drop in a turbine or in its stages falls to the share of the rotor is called the degree of reaction of a single-stage turbine or of a stage in a multi-stage turbine. The degree of reaction also shows what part of the work of expanding the gas in a turbine or its stage is accomplished in the rotor.

A stage in a turbine consists of one row of nozzle blades, usually called the nozzle (guide) ring, and one row of rotor blades next to it in the direction of the gas flow.

Both single-stage turbines and multi-stage turbines having a few successively arranged stages are used in various fields of engineering, including aviation.

The ratio of the peripheral velocity of the rotor U at the mean diameter d to the velocity of the gas at the exit of the nozzles c_1 is of great importance for effective turbine operation.

The maximum efficiency of a turbine or its stages is reached when the peripheral velocity of the rotor (depending on its mean diameter) is less than the velocity of the gas at the exit of the nozzles roughly by 1.4–2.2 times (depending on the degree of reaction). The maximum efficiency of a reaction turbine is usually more than that of an impulse turbine. This is the result of more moderate velocities of gas and therefore less hydraulic loss in the flow passage in the reaction turbine.

In aircraft gas turbine engines only reaction turbines are used as the more economical ones with less specific fuel consumption. Impulse turbines, simpler in construction, were used in turbo-superchargers to supercharge reciprocating aircraft engines. These turbines are also used in rocket engines to drive pumps delivering fuel to the combustion chamber.

Multi-stage turbine

The velocity of gas at the exit of the turbine nozzles is determined mainly by the adiabatic heat drop taking place in the nozzles, i.e. the heat drop that takes place in the nozzles in the absence of any addition of heat to the gas or extraction of heat from it. The larger the heat drop, the higher this velocity.

However, an excessive increase in the velocity of the gas at the nozzle exit and in other elements of the flow passage of a turbine can entail a substantial increase in hydraulic losses in the flow passage and a noticeable decrease in the efficiency of the turbine.

Besides, with a large heat drop in a turbine stage the peripheral velocity of the rotor corresponding to the maximum stage efficiency can become intolerable for reliable rotor operation. In this case it becomes essential to reduce the peripheral velocity of the rotor, which entails a decrease in the efficiency of the stage.

If the heat drop in a turbine is too great for efficiency, i.e. for a high stage efficiency, a two-stage or multi-stage turbine with two or more successively arranged stages is used (Fig. 30).

According to the way the pressure drop (the ratio of the pressure of the gas before entering the turbine to the pressure afterward) is achieved turbines are classified as pressure-compounded or velocity-compounded turbines.

In a pressure-compounded turbine the drop in pressure is achieved successively (from the first stage to the last) over all the stages and the pressure of the gas decreases gradually from the first to the last stage of the turbine.

Every pressure stage consists of a nozzle ring and a rotor in which the process of energy conversion is carried out in the same way as in the nozzle ring and rotor of an analogical (impulse or reaction) single-stage turbine.

In a pressure-compounded turbine with a uniform distribution of total

heat drop across the stages as the peripheral velocity of the rotor corresponding to the maximum turbine efficiency is less than that of a single-stage turbine with the same heat drop by $\sqrt{z}$ times (z—number of stages). For example, the peripheral velocity of a four-stage turbine is half that of a single-stage turbine.

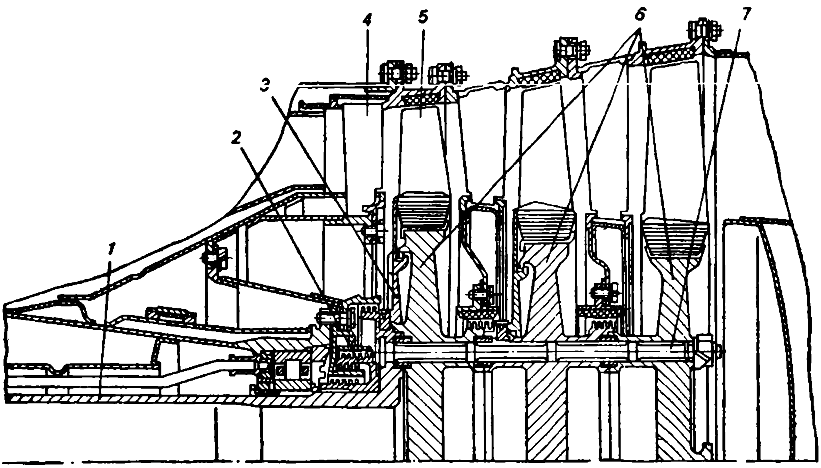


Fig. 30. A three-stage turbine:

1—shaft; 2—labyrinth packing; 3—thermal screen; 4—nozzle blade; 5 —rotor blade; 6—discs; 7—lightening pin.

The lower velocity of gas in the flow passage of a turbine and the better value of ratio U/c_1 enables a multi-stage pressure-compounded turbine to obtain a higher efficiency than a single-stage one with the same heat drop.

Two-stage and multi-stage pressure-compounded gas turbines are widely used in modern aircraft gas turbine engines. The efficiency of these turbines reaches 0.92 and above.

In contrast with the pressure-compounded turbine, the whole of the pressure drop in a velocity-compounded turbine takes place in the first stage and the resultant kinetic energy of the gas leaving this stage is gradually used up in the following stages.

This turbine has a lower efficiency than a pressure-compounded turbine with the same heat drop. Therefore in aircraft gas turbine engines, where efficiency is of primary importance, only pressure-compounded single and multi-stage turbines are used.

In rocket engines both velocity-compounded and pressure-compounded turbines are used to drive the pumps to deliver the propellant to the combustion chamber.

The first aviation gas turbines

A gas turbine was used for the first time in aviation in turbo-superchargers supercharging reciprocating engines. The products of combustion of the air-fuel mixture at high pressure and temperature were used as the working body. These products of combustion were exhausted from the engine cylinders not directly to the atmosphere but only after entering the gas turbine, where they were expanded and only then released to the surrounding medium.

The first gas turbine engine run on the exhaust gases from a reciprocating, four-stroke gasoline engine (not an aircraft engine) had been built and tested two to three years before the First World War began. The use of this turbine made it possible to reduce the specific fuel consumption of a power plant by about 8%.

The first turbo-supercharger to supercharge a reciprocating aircraft engine had been tested as early as 1918 though with unsatisfactory results. However, it was about 20 years before the serial production of turbo-superchargers and their wide-scale use began.

This delay in introducing turbo-superchargers is explained by the difficult operational conditions of: the exhaust valves of the reciprocating engine with a turbo-supercharger, the manifolds bringing the exhaust gases to the turbine, the rotor of the turbine and especially its blades.

Overcoming the difficulties involving the unsatisfactory operational conditions of the rotor had special significance for the introduction of the gas turbine in aviation.

While operating in the medium of hot gases the blades of a turbine are intensely heated, as a result of which they can withstand considerably smaller stresses than at normal temperature.

Besides, in the prolonged application of a load under high temperature conditions the metal undergoes plastic deformation even under comparatively small stresses. Moreover the longer the duration of load acting and the higher the stresses and temperature of the metal, the larger the magnitude of this residual deformation.

This phenomenon, known as creep, can lead to a situation where after a certain number of hours of service the blades of the turbine become so elongated that they start brushing against the engine casing.

Guaranteeing the satisfactory operation of blades under conditions of high temperatures and loads depended in the first place on the material they were made of. In the initial stage of turbo-supercharger development chromium-nickel steels with tungsten, molybdenum, vanadium or titanium additives were used as material for turbine blades.

The further development and perfection of turbo-superchargers, particularly an increase in service life, had to wait on new materials with superior qualities in the regime of high temperatures. To make turbine blades in

aircraft gas turbine engines nickel-based alloys (up to 70–80% of nickel) with a large content of chromium and smaller content of titanium, tungsten, molybdenum and aluminum are widely used.

The severe temperature conditions of the operation of turbine blades are eased by cooling them. The air compressed in the compressor is most often used as the coolant. To increase the strength of a blade the cross sectional area of the profile is increased from the tip to the root (by 3–5 times). The strength of the blades can also be increased by decreasing the lengths, i.e. by using large values of quantity θ (the ratio of the mean diameter of the rotor to the length of the blade is usually denoted by this Greek letter). In the earlier designs of aircraft turbo-superchargers this quantity had reached the value of 10 or more, while the length of the blades was 15–30 mm. In gas turbine engines the quantity θ is usually considerably smaller and the blades are much longer.

The turbines of a majority of the turbo-superchargers for supercharging reciprocating aircraft engines were impulse turbines. In the later designs of turbo-superchargers reaction turbines were also used due to the increasing heat drop. In gas turbine engines only reaction turbines are used since they are more efficient.

Power of gas turbine

The power of a gas turbine is the quantity of mechanical work it performs in a unit time.

The power is determined firstly by the mass rate of flow of the gas through the turbine, i.e. the mass of gas flowing through the turbine in a unit time; secondly by the adiabatic heat drop taking place in the turbine or adiabatic work of expansion of one kilogram of gas in the turbine which is the same thing; thirdly by the efficiency of the turbine, which is equal to the product of these three quantities.

The adiabatic heat drop in the turbine depends on the temperature of the gas at the turbine inlet and the ratio of the pressures of the gas at the inlet and exit of the turbine. The higher the temperature of the gas at the turbine inlet and the aforementioned ratio of pressures, the larger the adiabatic heat drop.

The ratio of the pressure of gas at the turbine inlet to that at the exit of the turbine is called the degree of expansion or pressure drop in the turbine.

The first aircraft gas turbines used in the initial stage of development of turbo-superchargers for supercharging reciprocating engines had a small power output equal to a few tens of horsepower. In the later designs of turbo-superchargers the power of the turbines reached several hundred horsepower.

The turbines of aircraft gas turbine engines develop much more power,

measurable not in tens and hundreds but in thousands and tens of thousands of horsepower. High power is also developed by the gas turbines used in astronautics. For example, the gas turbine driving the pumps to deliver fuel to the combustion chamber of the liquid propelled rocket engine $F = 1$, which was used in the first stage of the launch vehicle of the *Apollo* spaceships, develops a power of nearly 55,000 hp.

Rotational speed of gas turbine

The rotational speed of aircraft turbo-superchargers of the twenties and thirties of this century was roughly 25,000 to 30,000 rpm. Modern low-power aircraft gas turbines have still higher speeds.

But the powerful aircraft gas turbine engines usually operate at lower rotational speeds. This is because there is a larger mass flow rate of gas in a powerful turbine than in a low-power one. It is clear that the larger the mass flow rate of the gas through the turbine, the bigger the area of the flow passage for the gas has to be provided, other conditions remain the same, in particular the density of the gas at the inlet of the turbine and the heat drop it undergoes. This area is determined in the first place by the mean diameter of rotor d and the length of rotor blades l.

For simplicity we will assume that the length of a rotor blade is directly proportional to the diameter of the rotor. In this case, for example, a fourfold increase in the gas flow rate in the turbine is required to double the mean diameter of its rotor. If, in our example, the larger turbine operates at the same rotational speed as the smaller one then the tensile stresses due the centrifugal forces in the rotor blades of the larger turbine will be four times greater than in the other. It is quite natural that such increased stresses in the blades should produce an unfavorable effect on reliability and service life. In order to avoid this the larger turbine must operate at a lower rotational speed than the smaller one (in our example, at half the speed).

The lower rotational speed of the larger turbine makes possible greater efficiency compared to what it would have been if it had operated at the same rotational speed as the smaller turbine.

The concept of a gas turbine engine

A gas turbine of a very small size and weight is capable of developing very great power. For example, a turbine having only one stage with a mean diameter of rotor equal to 0.5 m can develop a power more than 10,000–12,000 hp. But for a turbine to work and develop so much power it is necessary to supply it with compressed and strongly heated gas whose flow rate through the turbine must correspond to its power. Consequently devices for compressing and heating the gas are necessary so as to ensure the turbine's operation.

A thermal machine that unites all these devices with a gas turbine and with their help converts the chemical energy of the fuel into mechanical energy is the gas turbine engine.

A complex of gas turbine and the devices that ensure its operation, not combined in one machine, is called a gas turbine plant.

Unlike the reciprocating internal combustion engine, where all elements of the working process are carried out mainly in one component of the engine, the cylinder, different elements of the working process in a gas turbine engine are carried out in different components of the engine.

These components are: the compressor, which compresses the air before its entry to the device for heating; a device for heating which is a combustion chamber where the compressed air and fuel enter and the combustion of the fuel-air mixture takes place; and the gas turbine proper where the products of combustion of the fuel-air mixture enter and are expanded.

Part of the energy of the products of combustion given out during expansion in the turbine is converted into mechanical work at the turbine shaft. Part of this work, and in certain types of gas turbine engine, for example in a turbo-jet engine, all the mechanical work at the turbine shaft is spent on rotating the compressor and driving the accessories as also on the mechanical losses in the turbine.

The remaining useful part of the mechanical work is transmitted (usually through a reduction gear) to the consumer, for example the aircraft propeller in a turbo-prop engine, the screw or propeller in a marine gas turbine engine.

The gases leaving the turbine possess a considerable amount of energy which can be used for various purposes. In aircraft gas turbine engines this energy is used to create the reaction thrust.

In some gas turbine engines and plants part of the heat of the gases leaving the turbine goes to heat the air compressed in the compressor before entry into the combustion chambers, which makes it possible to improve the engine's efficiency.

According to the working cycle gas turbine engines are classified as engines with continuous combustion at constant pressure and engines with intermittent (periodic) combustion at a pressure that increases during the combustion process, particularly with combustion at constant volume.

A gas turbine engine or a gas turbine plant of the first type has an open combustion chamber in which the compressed air and fuel enter continuously, the fuel-air mixture burns continuously and the products of combustion of this mixture continuously flow out of the chamber to the turbine (Fig. 31).

A compressor *1* sucks air from the atmosphere, compresses it in a particular pressure and delivers it to the combustion chamber *2* open at the sides for the air inlet and for exit of the products of combustion.

A liquid or gaseous fuel which, mixed with the air, burns at a constant pressure is delivered to the combustion chamber through a tube *3*. The products of combustion enter turbine *4* in which the conversion of their internal energy into mechanical work takes place. After leaving the turbine the products of combustion are given out to the atmosphere through an exhaust tube.

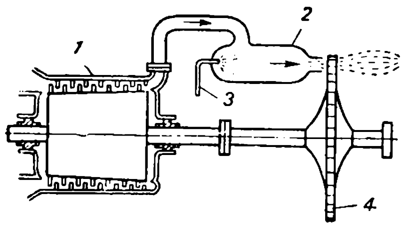


Fig. 31. Gas turbine plant with combustion at constant pressure.

The working of a gas turbine engine or a gas turbine plant with combustion at constant volume is more complicated. In the combustion chamber the valves, injector (in the case of liquid fuel) and electrical sparking device are located for periodic admission of air and fuel to the chamber, ignition of the fuel-air mixture and expulsion of the products of combustion from the chamber to the turbine.

In the earlier stages of development of gas turbine construction as much attention was paid to plants with combustion at constant volume as to plants with combustion at constant pressure.

Now gas turbine engines and plants with combustion at constant pressure, simpler in construction, have found wide application in various fields of engineering including aviation.

A substantial contribution to the development of gas turbines, gas turbine engines and plants with combustion at constant pressure was made by the workers of the Soviet aircraft industry who created and introduced serial production of a number of aircraft gas turbine engines. The names of many designers of gas turbine engines for indigenous aircraft are known not only in our country but also abroad.

A large contribution to the theory and practice of gas turbines, gas turbine engines and plants was made by Soviet scientists: V.M. Makovskii, V.V. Uvarov, I.I. Kirillov, G.S. Zhiritskii, Y.I. Shnae, B.S. Stechkin, P.K. Kazanjan, G.I. Zotikov, V.K. Abiants and others.

Combustion chamber

The combustion chamber of a gas turbine engine is located between the compressor and the turbine and together with the compressor belongs to that part of the engine called the gas-generator. This part of the engine produces a gas at high pressure (compared to the atmospheric) and temperature which is used as a working body in the other, expanding, part of the engine. The latter includes a gas turbine and, in aircraft engines, the exhaust system.

The necessary pressure of gas is provided by the compressor plus, in the

case of aircraft in flight, the intake system. The required temperature of gas must be provided by the combustion chamber in which the fuel is burned for this purpose. The oxygen of atmospheric air serves as an oxidizer.

However, the temperature of the products of combustion of the fuel-air mixture that can be obtained by efficient burning (by rapid, stable and total combustion) is too high to be used without prior cooling in the gas turbine. The materials used to make gas turbines cannot tolerate this high temperature because they do not possess the necessary strength and resistance to thermal stresses.

How is this reduction in the temperature of the products of combustion, necessary for reliable operation of a gas turbine, brought about?

In 1923 a Soviet designer, V.I. Bazarov, first suggested a method of organizing the working process in a combustion chamber applicable in all modern (both aircraft and other) gas turbine engines. The essence of this method is the division of the air entering from the compressor into the combustion chamber into two parts. One part, usually called primary air, participates in the combustion of fuel by providing it with the necessary quantity of oxidizer. The other, called the secondary air, is mixed with the hot products of combustion to cool them and so obtain the desired temperature of gas at the turbine inlet.

Here the quantity of primary air is regulated so that with the fuel it forms a combustible mixture whose composition ensures good combustion in the best way.

Let us remind you that the composition of a fuel-air mixture is characterized by the excess air ratio. This ratio, denoted by the Greek letter a, is the ratio of the actual quantity of air present in the mixture to the quantity of air theoretically necessary for the complete combustion of fuel contained in the mixture.

A flame tube *2* enclosed in the casing *1* is the main component of a combustion chamber (Fig. 32). The fuel delivered to the chamber burns in the tube. In it two characteristic zones are distinguished: the burning zone and mixing zone. Not all of the air G_B moving from the compressor into the combustion chamber enters the first zone, but only the smaller part of it, the primary air G_I. With the help of a fuel pump and at injector *3* the fuel is delivered here. A combustible fuel-air mixture is formed and the fuel contained in this mixture is burned. The products of combustion enter the second zone, where the secondary air G_{II} enters through inlets provided. Here they are mixed and the gaseous mixture thus formed moves to the turbine.

Gradual (stage-wise) supply of primary air along the length of the burning zone has great importance for correct organization of the working process in a combustion chamber. In this usually the total quantity of primary air somewhat exceeds the amount theoretically necessary, i.e. a_g is

more than unity. Not more than half of this theoretically necessary quantity of air ($\alpha_{fr} \leqslant 0.5$) enters directly at the beginning of the burning zone through a forward inlet.

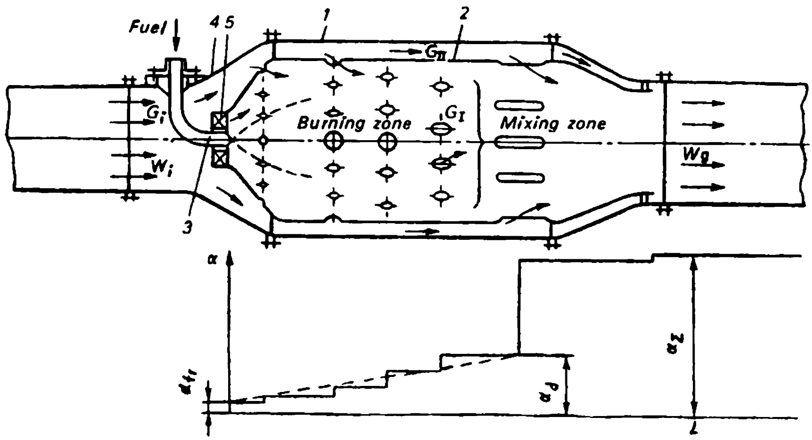


Fig. 32. Combustion chamber.

To stabilize the flame front and provide stable, continuous combustion a special device (or devices) are used called flame stabilizers. In combustion chambers of aircraft gas turbine engines a swirler *5* performs the function of a stabilizer.

To reduce the velocity of the air moving from the compressor into the combustion chamber, which is carried out in the diverging inlet section of the chamber, there is a diffuser *4*, which is very important for moderation of the conditions of fuel combustion.

The gas turbine is the basic type of engine of modern aviation

The aircraft gas turbine engine, like the reciprocating aircraft engine, is a heat engine used for moving and (or) holding the flying vehicle in the air.

The basic components of a modern aircraft gas turbine engine, which is the one with combustion at constant pressure, are: intake system, compressor, combustion chamber, gas turbine and exhaust (jet) nozzle.

The heat given out during the combustion of fuel in the combustion chamber is converted into mechanical work at the engine shaft and or the kinetic energy of the gas jet flowing from the engine into the surrounding medium.

Unlike stationary, marine and other gas turbine engines not meant for use on flying machines, in aircraft gas turbine engines the air entering it from the atmosphere in flight is compressed not only in the compressor but also in the intake system; the products of combustion are expanded

not only in the turbine, but also in the exhaust (jet) nozzle; the kinetic energy of the products of combustion leaving the turbine is no loss for the engine, but is used, together with the potential energy of this gas, to create reaction thrust.

Aircraft gas turbine engines are also characterized by a very low specific weight and small dimensions per unit of power.

In contrast to the reciprocating aircraft engine with propeller thrust in which the energy of the fuel converted into mechanical work at the engine shaft is utilized to obtain thrust with the help of an aircraft propeller, the aircraft gas turbine engine is totally or partially a jet engine.

When compared to the reciprocating aircraft engine the aircraft gas turbine engine makes it possible to obtain from one unit much more power. For the same power (thrust) its weight and frontal area are considerably less than those of a reciprocating engine. With increasing flight speeds these benefits of a gas turbine engine over a reciprocating engine become more and more noticeable.

It is these benefits that made the gas turbine engine the basic type of engine in modern aviation.

At low flight speeds the efficiency of an aircraft gas turbine engine is not higher than that of a reciprocating engine. However, at high flight speeds, especially at high altitudes, the efficiency of an aircraft gas turbine engine is greater than that of a reciprocating engine. A fuel of the kerosene type is most often used in aircraft gas turbine engines.

Those engines referred to as aircraft gas turbine engines are: the turbo-jet engine, turbo-prop engine and by-pass turbo-jet engine.

Before dealing with turbo-jet engines, introduced in aviation before other gas turbine engines, we will consider in detail the principle of operation of a jet engine.

Concept of a jet engine

An engine in which the energy of the fuel or any other energy is converted into the kinetic energy of a gas jet (or a stream of other working body) flowing out from the engine into the surrounding medium is called a jet engine. The force of reaction obtained from this is directly used as the driving force (thrust) for moving the flying or other transport vehicle on which the engine is mounted.

Let us explain in brief the origin of the reaction force. The action imparted during the operation of a jet engine to its working body brings about the acceleration of this body in a direction exactly opposite to the motion of the transport vehicle.

The reaction force exerted (according to Newton's third law) by the working body on the engine, and consequently on the vehicle on which it is mounted, is used to propel the vehicle. It is itself the reaction force. This

reaction force is the thrust of a jet engine created without the help of any additional propulsor.

Thus a jet engine bodily unites in itself an engine in the usual sense of the word and a propulsor.

The maximum thrust developed by a jet engine on increasing the flight speed over a wide speed range either does not fall at all, falls only negligibly or increases.

In modern aviation and astronautics various thermal jet engines creating thrust by conversion of heat into the kinetic energy of the gas stream flowing out from the engine into the surrounding medium are widely used.

The basic components of a thermal jet engine of any type are a device for heating the working body (combustion chamber) and a jet (exhaust) nozzle. Part of the heat given to the working body in the combustion chamber is converted in the nozzle into the kinetic energy of a gas jet.

The pressure of the gas at the inlet to the nozzle considerably exceeds the pressure of the surrounding medium. The expansion and corresponding increase in the velocity of the gas takes place in the nozzle.

The larger the mass of gas flowing out of the nozzle per unit time and the greater its speed at the exit of the nozzle (in the case of a rocket engine) or the greater the excess of this speed over the flight speed (in the case of an air-breathing engine) the greater the thrust of a thermal jet engine.

It is clear that the exhaust velocity of the gas from the jet nozzle is one of the most important parameters of a thermal jet engine. This velocity is determined mainly by the velocity and temperature of the gas at the inlet of the nozzle, the ratio of the pressure of gas at the inlet to that at the exit of the nozzle and the molecular weight of the gas. The higher the velocity and temperature of gas at the nozzle inlet, the larger the ratio of gas pressure at the inlet and exit of the nozzle and the lower the molecular weight of the gas, the higher the exhaust velocity of the gas.

The magnitude of this velocity for the thermal jet engines (not experimental ones) used in modern aviation and astronautics varies in flight within very broad limits (from some hundreds to some thousands of meters per second).

Depending on whether the exhaust velocity is subsonic or supersonic, the jet nozzle is distinguished as a converging (toward the engine exit) subsonic one or a converging-diverging supersonic one.

In the converging portion of a supersonic nozzle the velocity of the gas is less than the speed of sound, while in the diverging portion of the nozzle the gas is accelerated to supersonic velocities. The smallest section of a supersonic nozzle, in which the velocity of the gas is equal to the local speed of sound, is called the critical section.

The original shape of a supersonic nozzle is explained by the fact that

during expansion of the gas in the region of subsonic velocities the increase of gas velocity takes place more intensively than the corresponding decrease in density; in the region of supersonic velocities the increase of velocity takes place less intensively than the corresponding decrease in density. Therefore in the first case the increase of gas velocity requires a decrease in the flow section and in the second an increase in the flow section.

According to the working fluid and its dependence on (or independence of) the surrounding medium jet engines are divided into two basic classes: air-breathing engines, where the working body depends on the surrounding medium, and rocket engines, where the working body does not depend on the surrounding medium. The first are widely used in modern aviation, the second in rocket engineering and astronautics.

The fundamental problem of the theory of jet propulsion was worked out for the first time by the great Russian scientist N.E. Zhukovskii in his works *On the Reaction of Incoming and Outgoing Fluid* (1882–1886) and *On the Theory of Water Jet-propelled Vessels* (1908).

AIR-BREATHING JET ENGINE

An engine in which atmospheric air is used as a working body or source for it and atmospheric air also acts as an oxidizer during combustion of fuel in the engine is called an air-breathing jet engine.

The basic components of a thermal air-breathing jet engine of any type are: intake system (diffuser) to take in atmospheric air, supplying it to the engine with small losses and raising its pressure during the motion (flight) of the vehicle on which the engine is mounted; a device for heating the air passing through the engine, usually in the form of a combustion chamber in which the fuel-air mixture burns; and an exhaust (jet) nozzle for a smooth expansion and guided (axial) discharge of the products of combustion or heated air from the engine into the surrounding medium.

During flight at high speeds the most important task of the inlet section is to effectively use the kinetic energy of the free-stream airflow over the engine to raise the pressure of the air entering the engine. The most important task of the exhaust nozzle is the complete expansion of the products of combustion (or heated air) with minimum losses, because with this kind of expansion in a nozzle the engine develops maximum thrust.

The thrust created by an air-breathing jet engine with complete expansion of the products of combustion in the exhaust nozzle, i.e. with expansion down to a pressure equal to the pressure of the surrounding medium, is equal to the difference in momentum per second between the products of combustion discharged from the engine and the air entering the engine. It is expressed by the following formula:

$$P = m_g c_g - m_a c_0,$$

where P is the thrust; m_g is the mass of the products of combustion leaving the engine per second; c_g is their discharge velocity from the exhaust nozzle; m_a is the mass of air entering the engine per second; c_0 is the flight speed of the vehicle in which the engine is installed.

The main advantage of an air-breathing jet engine working on a chemical fuel over a rocket engine which also works on chemical fuel at the flight speeds and altitudes of the overwhelming majority of modern aircraft is its higher efficiency.

The main disadvantage of an air-breathing jet engine lies in the fact that it is possible to use it only over a limited range of flight altitudes. It does not possess the property inherent in a rocket engine to work at all speeds and at any altitude.

According to the way the process of compressing air is performed modern air-breathing jet engines are classified as compressorless engines and engines with compressors. In the first type of engines compression is carried out without the help of a compressor, utilizing the velocity head of the free-stream airflow over the engine in flight or by some other method; in the second type it is carried out under static conditions on the ground with the help of a compressor and in flight using both the velocity head and a compressor.

In aviation air-breathing jet engines with compressors are most widely used as being more efficient compared to the compressorless ones at the flight speeds of the overwhelming majority of modern aircraft. At these speeds the compression of air solely by the velocity head is quite insufficient to provide effective operation of the engine.

The basic components of an air-breathing jet engine with compressor, besides those mentioned earlier, are a compressor and an aggregate to drive it.

Jet engines are usually distinguished as air-breathing jet engines in which a reciprocating internal combustion engine is used to drive the compressor, and turbo-compressor air-breathing jet engines usually called turbo-jet engines. The turbo-jet engine's compressor is driven by a gas turbine. Since an air-breathing jet engine has considerably more weight and larger dimensions than a turbo-jet engine developing the same thrust, the air-breathing jet engine was not used in aviation. A turbo-jet engine, being lighter and of smaller size than the air-breathing jet engine, was preferred.

Among compressorless air-breathing jet engines the ramjet engine working on a cycle with combustion at constant pressure is of greatest interest. Its use at high flight speeds can be highly successful.

At high supersonic flight speeds, close to the hypersonic, the high air compression required for effective and efficient operation of air-breathing jet engines can be achieved only through the velocity head of the free-stream airflow over the engine. At these flight speeds the compressor becomes

unnecessary and the compressorless air-breathing jet engine can be used successfully.

However, the engine of an aircraft does not only work at the maximum or cruising speed. It must also provide for take-off, climb, acceleration up to maximum or cruising speed, intermediate flight speeds, descent and landing. In these regimes of engine operation the compressor may be very useful but in certain regimes, for example at take-off, it is simply essential.

Therefore for an aircraft whose maximum level or cruising speed by far exceeds the speed of sound and approaches the hypersonic a combined air-breathing jet engine uniting the compressorless air-breathing jet engine and the one with compressor is much to be desired.

A turbo ramjet engine belonging to this class of engines which can work either as a turbo-jet or as a compressorless ramjet engine is of unquestionable interest.

A large contribution to the theory of air-breathing jet engines has been made by Soviet scientists, especially academician B.S. Stechkin. His work *Theory of an Air-breathing Engine* published at the beginning of 1929 was the first scientific work in this field in the world and supplied the basis of the theory and design of air-breathing jet engines.

The theory of air-breathing jet engines was developed in further works by B.S. Stechkin and also in the works of the professors: N.V. Inozemtsev, T.M. Mel'kumov, Yu.N. Nechaev, I.I. Kulagin, K.V. Kholshchevnikov and others.

Turbo-jet engine

An aircraft gas turbine engine in which all the mechanical work at the turbine shaft is spent on rotating the compressor, on mechanical losses in the engine and in driving the accessories is called a turbo-jet engine.

In other words, in a turbo-jet engine the whole of the power developed by the turbine is spent to satisfy the requirements of the engine itself, while the useful mechanical energy it works out as a heat engine is the increase in kinetic energy of the working body flowing through the engine, i.e. the difference between the kinetic energy of the products of combustion leaving the engine and that of the air entering it.

Due to this increase in the kinetic energy of the working body a turbo-jet engine creates thrust, which is totally spent in propelling the flying vehicle in which it is installed.

Now between the compressor and the turbine the working body is strongly heated in the combustion chamber. So to achieve the same degree of compression of air in the compressor as that caused by the expansion of the products of combustion in the turbine the latter must develop a power considerably in excess of that required by the compressor. Therefore

in a turbo-jet engine in which the power of the turbine must only slightly exceed the power required by the compressor the gases (products of combustion) are expanded in the turbine not to a pressure equal to that of the air entering the compressor but to a significantly higher level.

Since under static conditions on the ground the pressure of the air entering the compressor is slightly lower than atmospheric pressure, while in flight it exceeds it, the gas is expanded in the turbine to a pressure greater than atmospheric pressure. The remaining drop of pressure is achieved in the jet nozzle and thanks to this the velocity of the products of combustion leaving the engine appears to be much higher than that at the turbine exit.

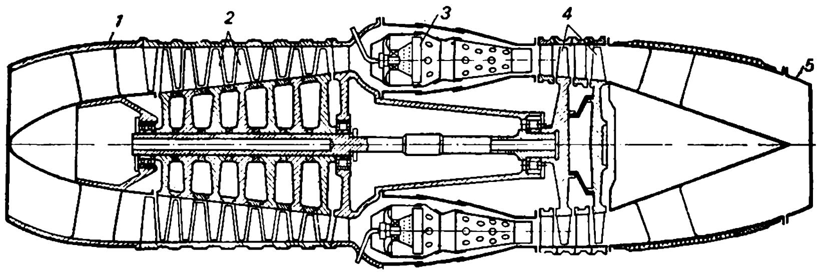


Fig. 33. Turbo-jet engine.

A gas turbine *4* (Fig. 33) drives the axial compressor *2*.

The air striking the engine in flight is slowed down and enters the compressor through the intake system *1*. During retardation the pressure of air is increased due to the velocity head.

In early turbo-jet engines the degree of compression of air in the compressor in the maximum regime of engine operation under static conditions on the ground was about 3. In modern turbo-jet engines it is from 4–5 to 12 and more. The overall degree of compression in the intake system and compressor in flight at supersonic speeds reaches 30–40 and more.

The compressed air from the compressor enters the combustion chamber *3* where the liquid fuel is continuously delivered through an injector. On starting the engine the fuel is ignited with the help of an electrical ignition system. During engine operation the ignition system is not required, and the flame in the combustion chamber lit on starting the engine is maintained by continuous delivery of fuel and air into it.

In the combustion zone of the chamber the temperature of the gas is roughly 1,600–2,000°C and at the exit of the chamber 500–1,000°C or more, depending on the type of engine and the regime of operation. At this temperature, with pressure approximately equal to that of the air leaving the compressor, the gas enters the turbine and is expanded in it to the pressure at which the power of the turbine slightly exceeds that required by the compressor.

Gas at this pressure leaves the turbine and enters the exhaust system in which, more accurately in whose basic component, exhaust (jet) nozzle 5, further expansion of the gas is carried out down or close to atmospheric pressure.

The expansion brings about a significant increase in the kinetic energy of the gas discharging from the nozzle into the surrounding medium in comparison with the kinetic energy of the gas leaving the turbine.

In modern turbo-jet engines the velocity of gas leaving the nozzle is roughly from 500 to 1,000 m/sec in the maximum regime of engine operation under ground static conditions.

With increasing flight speed the mass flow rate of the gas and its exhaust velocity from the jet nozzle increase. However, the exhaust velocity of the gas increases more slowly than the flight speed. Therefore with increasing flight speed the excess of exhaust velocity over flight speed decreases.

As a result, in the flight speed range where the mass flow rate of gas varies at a higher rate than the excess of exhaust velocity of gas over flight speed, an increase in flight speed increases the thrust of the turbo-jet engine. On the other hand, in a flight speed range where the excess of exhaust velocity over flight speed varies at a higher rate than the mass flow rate, an increase in flight speed decreases the thrust of the turbo-jet engine.

In comformity with this the thrust of a turbo-jet engine varies in the following manner: In the region of subsonic flight speeds an increase in speed at first leads to some decrease in thrust, after which it begins to increase. This growth continues in the region of supersonic flight speeds up to a certain speed, but not indefinitely. Its magnitude depends on a number of factors: particularly on flight altitude, degree of compression in the compressor and temperature of the gas at the turbine inlet. A further increase in speed leads to a decrease of thrust.

Finally, at high supersonic flight speeds whose magnitude is equal to the exhaust velocity of the gas from the jet nozzle the thrust becomes equal to zero.

One of the main reasons for the decreasing thrust of a turbo-jet engine at high supersonic flight speeds is the heating up of air entering the engine. The higher the flight speed the stronger this heating.

To make clear how the heating up of the air entering the engine decreases its thrust, let us take for example an extreme case. Let us assume that the flight speed is increased so much that the heating of the air entering the engine produces an air temperature on leaving the compressor equal to the maximum temperature for gas at the turbine inlet permissible for reliable operation. In this case further heating of the air in the combustion chamber due to the energy of burning fuel would inevitably lead to an unacceptable temperature of gas at the turbine inlet. It would not be

possible to burn fuel in the combustion chamber and without this energy a turbo-jet engine cannot operate and develop thrust. Thus excessive heating of air entering a turbo-jet engine can decrease the engine thrust right down to zero.

The scheme of an aircraft turbo-jet engine was first suggested by N. Gerasimov, an engineer, who patented his invention more than 60 years ago. The first serial turbo-jet engine produced in the years 1944–1947 possessed technical specifications enabling construction of aircraft with flight speeds of 850–950 kmph and more.

Under static ground conditions they developed a thrust from roughly 700–800 to 1,700–1,800 kg and more; their specific weight was approximately from 0.45 to 0.9; specific frontal thrust was from 800 to 2,000 kg or more per unit square meter frontal area of the engine; specific fuel consumption was from 1.05 to 1.4–1.5 kg fuel/hr kg thrust.

At flight speeds of 850–950 km/hr these engines had important advantages over reciprocating engines regarding power developed in one unit, specific weight and specific frontal thrust.

The rapid development of the turbo-jet engine made it possible to achieve even in the early post-war years a flight speed equal to the speed of sound and later to surpass it by a wide margin.

On December 26, 1948, a flight speed equal to the speed of sound was for the first time reached on the aircraft "176" built by the design bureau guided by S.A. Lavochkin with the VK–1 engine of V.Y. Klimov's design. Two years later the flight speed of the aircraft Mig–17 exceeded the speed of sound.

At supersonic flight speeds the turbo-jet engine surpasses reciprocating engines also in respect of economy. This comparison could be made only by way of calculation because in practice it was not possible to attain either supersonic speed or even a speed equal to the speed of sound with the reciprocating engine.

It is not surprising therefore that it was the turbo-jet engine that was responsible to a large extent for creating supersonic aviation at the end of the first half of the present century. Currently turbo-jet engines are used abroad on aircraft with flight speeds of three times the speed of sound or more. The thrust that the modern turbo-jet engine develops in one unit has reached 10 tons or more. It has lowered the specific weight of engines compared to the engines of 1944–1947 by many times and increased their specific frontal thrust. The engine has become much more reliable and durable. The specific fuel consumption has been significantly reduced.

Single-spool and twin-spool turbo-jet engines

Turbo-jet engines with a small degree of compression (roughly five under static ground conditions) are usually made single-spool. They have

a single stage turbine driving a single-spool (more often axial, and seldom centrifugal) compressor.

Engines with a degree of compression of six or more (under static ground conditions) are made in other countries single-spooled or double-spooled. In the first case, they have a two or three-stage turbine driving a single-spool multi-stage axial compressor and in the latter two turbines, each of which drives a group of stages of the compressor.

The majority of modern turbo-jet engines have axial compressors because they have a higher efficiency and allow a much higher degree of compression to be achieved than a centrifugal compressor, thus ensuring more efficient engine operation and a correspondingly smaller specific fuel consumption. Besides, a turbo-jet engine with an axial compressor has more specific frontal thrust than one with a centrifugal compressor.

We will remind you that the axial compressor is the compressor in which the main movement of the flow of compressible air takes place in a plane parallel to the axis of rotation of the compressor rotor.

The conversion of energy in one stage of an axial compressor takes place in the same way as in the reverse stage of an axial reaction turbine, i.e. in the stage of a turbine where the gas moves and changes its state not in the usual direction from the nozzle rim to the rotor, but in the reverse direction.

In an axial compressor the air enters the channels between the rotating rotor blades. While it flows around them these blades transfer to the air the energy necessary for its compression. Due to this energy the compression of air takes place first in the channels between the rotor blades and thereafter in the channels between the stator blades located just behind the rotor blades along the path of the air. The stator blades are called straightener blades since they totally or partly straighten the airflow deviated by the rotor blades.

The rise in air pressure achieved in one stage is small. Therefore axial compressors are made multi-staged (Fig. 33). Axial compressors of a modern turbo-jet engine have six or more stages.

The geometrical configuration of the stages of an axial compressor corresponds in the best possible way to the basic (design) regime of its operation. In this regime all stages of the compressor operate steadily and consistently among themselves, ensuring the required degree of compression and high efficiency. However, in off-design regimes the geometrical configurations of the stages are no longer the best, consistency among the stages is destroyed and efficiency is reduced. On decreasing the airflow through a compressor below a certain value, lower at low rotational speeds under given atmospheric conditions and flight speed, compressor operation becomes unstable and a dangerous phenomenon called surge arises.

Compressor surge is characterized by steep oscillations of the head

and flow rate of the air leading to vibration of the blades and the compressors which is dangerous for the compressor itself and other components of the power plant. Surge also brings about fluctuations of the airflow at the entrance to the combustion chamber which leads to unstable combustion in the chamber.

An effective way to improve the operation of a multi-stage axial compressor in off-design regimes is to use a twin-spool (twin-rotor) compressor (Fig. 34). It consists of two consecutive groups of stages (cascades) with separate drive for each group from separate turbines. Such a compressor works better in off-design regimes than a single-spool one with the same designed degree of compression. Moreover, this advantage is more noticeable the higher the degree of compression.

Since the shafts of the turbine are not coupled to each other mechanically they can be rotated at different rotational speeds.

In construction a twin-spool turbo-jet engine is more complicated than a single-spool one with the same design parameters but then it has a wide range of regimes of stable operation of compressor, lower specific fuel consumption and lower temperature of gas at the turbine inlet in cruising regimes, especially with full throttling of the engine, and also a somewhat better response.

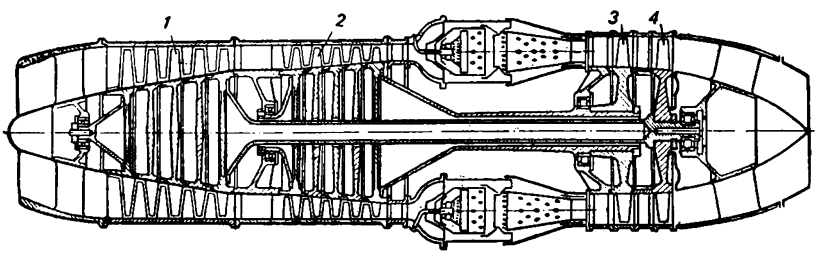


Fig. 34. Twin-spool turbo-jet engine:

1—low-pressure cascade; 2—high pressure cascade; 3—turbine driving the high-pressure cascade; 4—turbine driving low-pressure cascade.

To improve the operation of a single-spool multi-stage axial compressor under off-design regimes (with a degree of compression, under ground static conditions, of six or more) it is made adjustable.

One of the most widely used methods of adjustment is application of rotating straightener blades in one or two groups or stages. On varying the regime of engine operation the rotation of these blades makes it possible to set them in a position that suits every regime in the best way.

The simplest method of adjustment of a compressor to prevent surge is to by-pass a portion of the air from one or several intermediate stages of the compressor to the atmosphere.

In some turbo-jet engines designed to operate at a wide range of flight

speeds from low subsonic to high supersonic by-passing of part of the air from the last stage of the compressor into the afterburner is used to regulate the degree of compression in the compressor in flight.

Turbo-jet engine with an afterburner

A combustion chamber meant for additional burning of fuel after the turbine stage to increase the thrust is called an afterburner (Fig. 35).

The main components of an afterburner are a diffuser (diverging passage), in which the high velocity of the gas leaving the turbine is reduced to a value at which it is possible to carry out efficient burning of fuel, and the combustion chamber itself, to which an adjustable nozzle is fitted, i.e. the nozzle is provided with a device to vary its geometry during engine operation.

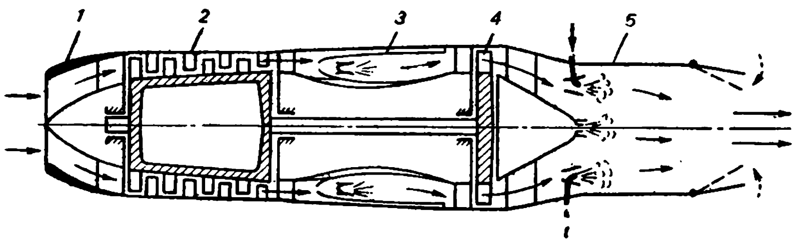


Fig. 35. Turbo-jet engine with afterburner:

1—intake system; 2—compressor; 3—main combustion chamber; 4—turbine; 5—afterburner.

In an afterburner are located: arrangements for the delivery and ignition of fuel, flame stabilizer (stabilizers) providing stable combustion of fuel and an antivibration screen. The purpose of the screen is to eliminate vibratory combustion of fuel followed by unpleasant noise and shaking that might destroy the engine.

Depending on whether the afterburner is designed for operation with one particular degree of reheat of gas or with a variable degree of reheat it is classified as a single regime or multi-regime afterburner. The degree of reheat of gas in an afterburner is the ratio of the absolute temperature of the gas at the exit of the afterburner to that at the inlet.

In order to prevent overheating of turbine blades on switching on the afterburner it is necessary to increase the flow area of the jet nozzle in the following manner: the higher the degree of reheat, the larger must be the increase in the flow section area.

If a turbo-jet engine has not a single-regime but a multi-regime afterburner it is necessary to regulate the jet nozzle not only on switching it on and off but also during variation of the degree of reheat of gas.

The combustion of fuel in an afterburner takes place due to the excess

of oxygen in the products of combustion leaving the turbine. Due to the increased temperature of the gas at the inlet of the jet nozzle the exhaust velocity of gas leaving the jet nozzle increases. In turn this brings about a corresponding increase in the thrust developed by the engine.

The use of an afterburner enables the thrust of a turbo-jet engine to be increased under static ground conditions by 30–50% or more. Here the specific fuel consumption increases by roughly 70–130%.

The effectiveness of burning fuel in the afterburner increases with increasing flight speed, which makes it possible to increase the thrust at supersonic flight speeds with a comparatively small increase in the specific fuel consumption.

At high supersonic flight speeds the use of an afterburner enables the thrust of a turbo-jet engine to be increased several times. An afterburner variable-area supersonic intake diffuser and jet nozzle are the typical components of a modern turbo-jet engine designed for such flight speeds.

Supersonic intake diffuser and jet nozzle

An intake system providing for efficient use of the kinetic energy of a free-stream supersonic airflow over an engine to raise the pressure of air entering the engine is called a supersonic intake diffuser.

A fixed-area diffuser performs this task successfully with a low external (frontal) resistance but ensures stable operation only in a narrow range of regimes to which the geometrical dimensions and shape of the diffuser correspond. As the operation regime starts to leave this range the diffuser starts operating less efficiently, while at a large off-design regime it becomes unstable. "Surging" develops or, less dangerous, "buzzing."

Surging causes vibrations which are dangerous for the strength of the diffuser itself and for other components of the power plant. It also causes air turbulence at the inlet to the combustion chamber and disturbs the stability of the combustion in it. The latter can lead in some cases to the quenching of the flame in the combustion chamber and shutting-off of the engine. In other cases it can result in an increase in the gas temperature at the turbine inlet and overheating of the blades.

For a supersonic intake diffuser to operate efficiently over the whole range of flight regimes it is made adjustable. One principle of adjustment lies in the fact that in every regime the quantity of air flowing through the diffuser must be consistent with the quantity of air required for engine operation with stable working of diffuser and minimum losses. The adjustment is carried out by changing the geometry of the diffuser, particularly by varying the area of its minimum flow section and also by admitting to the diffuser additional air from the atmosphere or, conversely, by discharging unnecessary air from the diffuser to the atmosphere.

In modern aviation an intake diffuser with a profiled central body that

is movable from the diffuser channel toward the free-stream airflow is often used (cf. Fig. 37). Displacement of the central body regulates the diffuser in an off-design regime of operation.

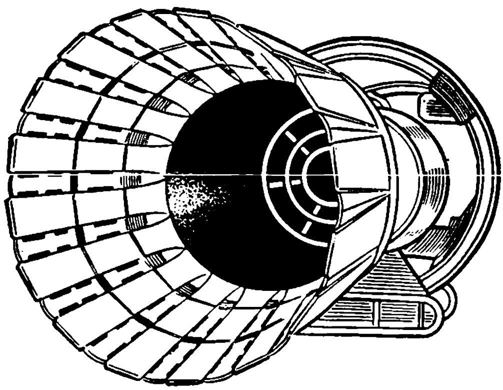


Fig. 36. Supersonic jet nozzle of turbo-jet engine J79-17.

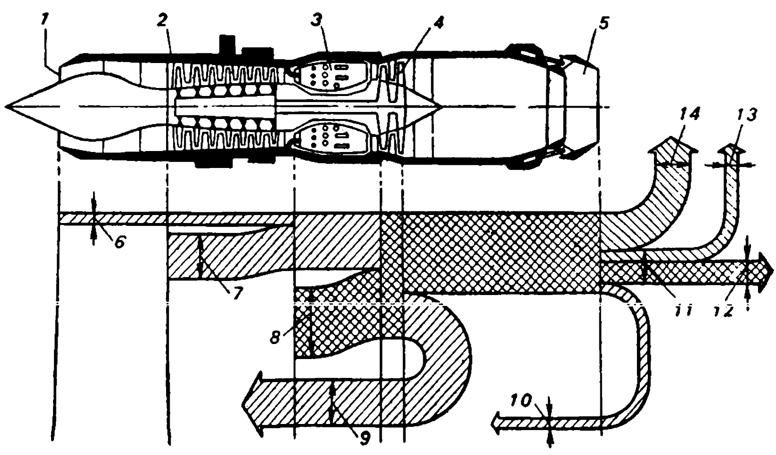


Fig. 37. Energy balance of a turbo-jet engine:

1—diffuser; 2—compressor; 3—combustion chamber; 4—turbine; 5—nozzle; 6—energy of entering air; 7 and 8—energy imparted to the air; 9—energy given out by the gas in turbine; 10—energy equal to that of entering air; 11—energy worked out by the engine as a heat machine; 12—useful energy; 13—waste part of energy 11; 14—heat of exhaust gases.

In the case of a turbo-jet engine with afterburner designed for high supersonic flight speeds the adjustment of nozzle (Fig. 36) is carried out not only while switching the afterburner on and off but also whenever necessary to provide at all flight speeds and altitudes and in all regimes of engine operation a complete or near-complete expansion of gas in the nozzle with minimum loss. For this purpose the geometry of the nozzle,

particularly the area of minimum (critical) exit sections, and also the shape of its diverging portion are varied in flight.

Energy balance of turbo-jet engine

In Fig. 37 are shown in the form of a stream the amount of energy *6* possessed by air entering the engine and the amount of energy imparted to the working substance by the compressor *7* and the combustion chamber *8*.

After gaining energy (*6+7+8*) the gas leaves the combustion chamber and enters the turbine. Here it gives out part of its energy *9* to drive the compressor and the accessories of the engine and as heat lost to the surrounding medium through the turbine casing and on the delivery of heat to the air cooling blades and the disc of the turbine.

From the turbine the gas leaves with an energy equal to *6+7+8−9* and at the exit of the jet nozzle it possesses (in the case of engines without an afterburner) somewhat less energy due to loss of heat to the surrounding medium through the walls of the nozzle and on the way from the turbine.

Thus the working body passing through the engine increases its energy output (mechanical and thermal) roughly by *7+8−9*. However, not all the increase in the energy of the working body is utilized. The larger part *14* is lost for the engine and flying vehicle because it is the heat carried out of the engine with the products of combustion. The remaining part of energy *11* is the mechanical (kinetic) energy turned out by the engine as a heat machine. It does not exceed on the ground one-third, and in flight one-half, of the chemical energy of the fuel burned in the engine.

However, only part of this energy *12*, insignificant at low flight speeds but reaching roughly 20-30 per cent or more of the chemical energy of the fuel burned in the engine at high flight speeds, is used to propel the flying vehicle. The products of combustion carry away with them the remaining part of the energy *13*. This energy lost for the flying vehicle is the kinetic energy of the products of combustion leaving the engine in their motion not with respect to the engine, but relative to the surrounding medium.

In the case of an engine with an afterburner additional energy is imparted to the working body. Therefore the energy of the gas at the exit of the jet nozzle is equal to the sum of the energy of gas leaving the turbine and the additional energy imparted to it in the afterburner minus the heat lost to the surrounding medium through the nozzle component. For this engine, the energy used to propel the flying vehicle forms a smaller (by 1.5–2 times at low and 1.1–1.3 times at high flight speeds) part of the chemical energy of the fuel burned than for an engine without afterburner.

Turbo-prop engine

A turbo-prop engine possesses greater efficiency than turbo-jet engine at

subsonic flight speeds. In this engine the power developed by the turbine (turbines) is used not only to drive the compressor and accessories but also to drive the propeller which is the main propulsor.

Unlike a turbo-jet engine, which is a wholly jet engine, a turbo-prop engine is an engine with combined thrust which is made up of jet thrust and the thrust created by the propeller.

The creation of thrust with the help of an aircraft propeller is more effective under static ground conditions and at low and medium flight speeds, while at high speed the thrust from gas jets is more efficient. The fields of application of turbo-prop and turbo-jet engines are therefore different.

The main components of a turbo-prop engine (Fig. 38) are the intake system *1*, compressor *2*, combustion chamber *3*, gas turbine *4*, exhaust system *5* and reduction gear *6*. Since the rpm of the aircraft propeller *7* at which it works most efficiently is much smaller than that of the turbine a reduction gear reduces the number of rotations of the propeller by roughly 5–15 times compared to that of the turbine.

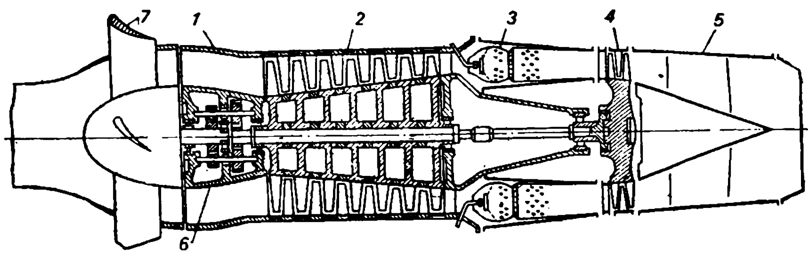


Fig. 38. Turbo-prop engine.

In the turbine of a turbo-prop engine a considerably larger drop in pressure is effected than in the turbine a turbo-jet engine. Due to this it is always multi-stage. The number of stages is as much as six and never less than two.

A turbo-prop engine is either a single-spool one with one common turbine for compressor and propeller or a twin-spool one with two different turbines, kinematically separate from each other, one of which serves as the drive for the compressor and the other for the propeller.

In some twin-spool turbo-prop engines one turbine brings into motion some of the compressor stages and the other the propeller and the remaining stages.

A turbo-prop engine usually has either an axial or a combined compressor (an axial and, coupled to it, centrifugal compressor). Low-power engines are made with both axial and centrifugal compressor.

The principle of operation of a turbo-prop engine is as follows: as in

the case of a turbo-jet engine during flight the atmospheric air is compressed successively first in the intake system and later in the compressor from which it enters the combustion chamber. Due to the lower speed of the flying vehicles on which turbo-prop engines are installed the compression of air in the intake system is weaker than in the turbo-jet engine.

As in the turbo-jet engine the ignition of a fuel-air mixture during starting of the turbo-prop engine on the ground is actuated from a separate source, while during subsequent independent engine operation the flame is maintained by the continuous delivery of fuel and air into the combustion chamber. The products of combustion from the chamber enter the turbine where, by expanding, they perform the work that is used to drive the compressor and the propeller. From the turbine the products of combustion enter the exhaust system.

In contrast to the turbo-jet engine, in which the gas is expanded to a pressure considerably exceeding the atmospheric and further expansion of the gas takes place in the nozzle, in the turbine of a turbo-prop engine it is possible to have the expansion of gas down to a pressure slightly exceeding the atmospheric, equal to it or even less than the atmospheric.

In the first case the subsequent expansion of gas takes place in the exhaust nozzle, in the second it is completed in the turbine and the gas is not expanded in the nozzle and in the third the gas is compressed in the exhaust system to atmospheric pressure.

The smaller the pressure of gas at the turbine exit the larger the fraction of the energy that it possessed at the inlet of the turbine that can be used to rotate the aircraft propeller.

The velocity of the gas at the nozzle exit is more than that of the air entering the engine, as a result of which a reaction thrust is created. The total thrust of a turbo-prop engine is made up of the thrust of the propeller (the main part of the total thrust) and the jet thrust.

The main advantages of a turbo-prop engine when compared with a turbo-jet engine are much larger take-off thrust for the same fuel consumption, degree of compression in the compressor and turbine inlet temperature, and a considerably lower specific fuel consumption at low and medium subsonic flight speeds.

Turbo-prop engines are used on aircraft with flight speeds up to 700–800 kmph, including the Soviet aircraft TU–114, Il–18 and the giant An–22 which are well known not only here but also abroad.

Our motherland takes the palm in the field of the turbo-prop engine. The idea of such engines had been suggested for the first time in 1914 by Lieutenant M.N. Nikol'skii. Nikol'skii's engine had a combustion chamber in which a combustible mixture consisting of two liquid components (turpentine and nitric acid) were burned and a three-stage gas turbine used the products of combustion of the mixture as its working body. The turbine

drove the aircraft propeller while the exhaust gases created additional reaction thrust.

In 1923 a Soviet designer, V.I. Bazarov, worked out the design of an engine close to a modern turbo-prop engine. Air was used as the working body. The power of the turbine was utilized to drive a centrifugal compressor and the aircraft propeller.

By-pass turbo-jet engine

A third type of gas turbine engine widely used in modern aviation is the by-pass turbo-jet engine. In this engine not all the air entering the engine is used as a working body in the turbine. Only a part of it is used, compressed initially in the main compressor and heated in the main combustion chambers.

The gas leaving the turbine is further expanded in the jet nozzle, acquiring a velocity exceeding the flight speed, thus creating thrust. The gas-dynamic contour that includes the main compressor, the main combustion chamber, gas turbine and jet nozzle is called the primary (inner) duct.

The remaining part of the air entering the engine passes through an external annular duct called the secondary (outer) duct. Acceleration of this part of the air necessary to create thrust is actuated with the help of a low-pressure compressor (fan).

In a by-pass turbo-jet engine the power developed by the turbine is used up in driving the main and low-pressure compressors and accessories.

The thrust of a by-pass turbo-jet engine (Fig. 39) consists of two parts: the thrust created by the primary duct and the thrust created by the secondary duct due to the energy supplied to it by the primary duct (gas turbine).

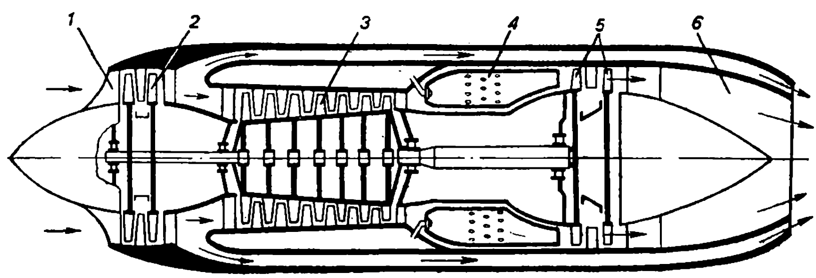


Fig. 39. By-pass turbo-jet engine:

1—intake part; 2—low pressure compressor (fan); 3—inner duct compressor; 4—combustion chamber; 5—turbine; 6—jet nozzle.

The primary duct of the engine works in the same way as a turbo-jet engine with the usual scheme. However, due to fact that it gives part of the energy of the gas flowing through it to the secondary duct the exhaust

velocity of the gas from the jet nozzle and correspondingly the thrust developed by the primary duct happen to be lower than those of a turbo-jet engine with the usual scheme having the same flow rate of air, degree of compression in the compressor and turbine inlet temperature as the primary duct.

The thrust of the secondary duct depends on the flow rate of the air passing through it, the amount of energy delivered to it per unit time by the primary duct and the flight speed.

Depending on the location of the low-pressure compressor (fan), there exist two different types of by-pass turbo-jet engines: forward-fan and after-fan engines. In the first case the fan compresses all the air entering the engine, in the second only the air of the outer duct.

By-pass turbo-jet engines are usually made two-spool or even three-spool.

In widely used two-spool engines with forward or after fans the high-pressure turbine (the first turbine along the flow of gas) drives the main compressor while the low-pressure turbine drives the fan.

In three-spool engines with forward fan, recently developed abroad, the high-pressure, low-pressure and intermediate-pressure turbines drive the high-pressure (the last along the airflow), low-pressure (fan) and intermediate-pressure compressors respectively.

After leaving the low-pressure turbine the gas is mixed with the air of the outer duct (mixed flow by-pass turbo-jet engine) and flows out from the mixing chamber through a common nozzle. In many by-pass turbo-jet engines the streams are not mixed in the engine (Fig. 39).

A by-pass turbo-jet engine can be boosted by burning fuel in an additional (afterburner) chamber which is located in the primary or in the secondary or in both ducts. In a mixed-flow engine the afterburner can be common for both ducts.

The main advantages of a by-pass turbo-jet engine over a turbo-jet engine are the smaller specific weight with respect to the take-off thrust, lower specific fuel consumption over a wide range of subsonic flight speeds and also less noise. The drawback of a by-pass turbo-jet engine lies in its smaller specific frontal thrust.

A by-pass turbo-jet engine surpasses the turbo-jet engine in economy at low and medium subsonic flight speeds although it yields to it in this respect at transonic and supersonic flight speeds. In addition the by-pass turbo-jet engine does not require an aircraft propeller and does not have a reduction gear, which reduces the weight of the power plant by comparison with the turbo-prop engine.

In a modern by-pass turbo-jet engine under static ground conditions in the maximum regime of engine operation the degree of compression of the air in the primary duct varies within wide limits roughly from 8–10 to 20–

25 and more, while the turbine inlet temperature of the gas reaches 1,000–1,100°C or more.

For efficiency and economy of by-pass turbo-jet engine operation the distribution between the ducts of the total quantity of air entering the engine is of great importance. The larger the airflow through the secondary duct the higher the efficiency of the engine at subsonic flight speeds.

A by-pass turbo-jet engine with a flow of air through the secondary duct equal to (or more than) the flow of air through the primary duct and correspondingly with a small degree of compression in the secondary duct (about 1.2 to 2.5) is called a turbo-fan.

According to published data, turbo-fan engines with a flow of air through the secondary duct five times larger than through the primary one and having a degree of compression in the primary duct of 22–27 have a specific fuel consumption of roughly 0.62 kg fuel hr/kg thrust at an altitude of 11 km and flight speed of 900–960 km/hr. This is considerably less than that for the modern turbo-jet engine in the same flight regime. It is like using roughly 35% of the chemical energy of the fuel burned in the engine to propel the flying vehicle.

A constructional scheme for a by-pass turbo-jet engine was suggested for the first time by a famous Soviet designer, A.M. Lyul'ka, in 1937.

By-pass engines are used on different subsonic aircraft including the new Soviet passenger aircraft Tu–134, Tu–154, Il–62 and Yak–40. On the aircraft Tu–154, with a cruising speed of 850–1,000 km/hr at an altitude of 11–12 km, three by-pass turbo-jet engines of N.D. Kuznetsov's design are mounted. On the aircraft Yak–40 there are three engines designed by A.G. Ivchenko.

The by-pass engine is used not only in civil but also in military aviation. Specifically it is mounted on a number of new foreign military aircraft including a vertical take-off and landing fighter-bomber and a heavy military-transport aircraft with a take-off weight of more than 300 tons. On the first there is one turbo-fan engine with swiveling jet nozzle making it possible to change the direction of thrust. The latter has four turbo-fan engines. By-pass engines with afterburners are used on some supersonic military aircraft.

The by-pass turbo-jet engine is also used on one-man flying vehicles. This vehicle, with a jet engine located behind the pilot's back, received the name "jet belt". According to foreign literature different versions of the "jet belt" with a rocket or by-pass turbo-jet engine have been manufactured and tested in recent years, enabling a man to rise from the ground for a short-duration flight. One-man vehicles with a by-pass turbo-jet engine have shown the best results in range and duration of flight due to their much higher efficiency compared to a rocket engine.

Ramjet engine

A ramjet engine is a compressorless air-breathing engine with a continuous combustion of fuel at roughly constant pressure. Atmospheric air whose oxygen is used as an oxidizer enters the engine and the products of combustion flow out of the engine into the surrounding medium at a velocity exceeding the flight speed, due to which thrust is created.

The compression of air that precedes the combustion of fuel is effected wholly by the velocity head of the free-stream airflow over the engine. As a result of this a ramjet engine does not develop any thrust under static conditions and can operate effectively only at high flight speeds.

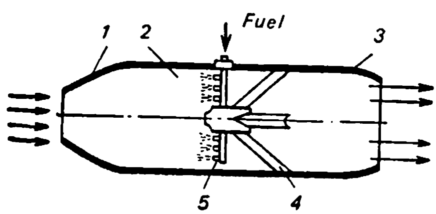


Fig. 40. Ramjet engine.

The main components of a ramjet engine (Fig. 40) are diffuser *1*, in which the compression of air entering the engine takes place, combustion chamber *2* with injectors *5* for delivering fuel, ignition devices and flame stabilizer *4* and jet nozzle *3* from which the products of combustion flow out to the surrounding medium.

The ramjet engine, according to foreign literature, is capable of operating and developing useful thrust at higher speeds and higher altitudes than the turbo-jet engine for a smaller specific weight under these conditions. This is explained by the absence of compressor and turbine, which makes it possible to reduce substantially the weight of the engine and to heat the gas in the combustion chamber to much higher temperatures than are permissible for reliable turbine operation in a turbo-jet engine. At very high flight speeds the air entering the ramjet engine is strongly heated during its retardation down to subsonic speed in the diffuser.

Further heating of the air in the combustion chamber due to the chemical energy of the burning fuel yields a very high temperature for the products of combustion. But the higher the temperature the larger the part of the products of combustion that dissociates, the larger the proportion of molecules that break up into simpler molecules and atoms.

Part of the heat given out during the combustion of fuel is spent on the process of dissociation in the engine. The higher the temperature of the products of combustion, the larger the part of this energy spent on dissociation. At a temperature of products of combustion of 2,700–2,900°C corresponding to a flight speed of roughly seven times the speed of sound, almost half of the total energy of the heat given out in the combustion chamber goes on dissociation. At a temperature of 3,200–3,400°C corresponding to an even higher flight speed almost all the heat given out in the

combustion chamber is spent on dissociation. Naturally only the very small remaining part of this heat can be used to heat the air in the combustion chamber, to accelerate the products of combustion in the jet nozzle and thus create thrust. As a result the engine can develop only a small thrust.

To reduce the excessively high heat loss on dissociation to a substantial degree it is advisable in ramjet engines designed to operate at very high flight speeds to slow down the air entering the engine not to a subsonic speed but to a much higher speed in the supersonic range. In this case the burning of fuel in the combustion chamber takes place at the supersonic speed of the gas flowing through it. Such an engine is called a ramjet engine with supersonic combustion in contrast to the usual ramjet engine with subsonic combustion.

The drawbacks of a ramjet engine in comparison with the turbo-jet engine are the absence of thrust under static conditions and also the low efficiency of operation at subsonic and moderate supersonic flight speeds. Therefore on flying vehicles with high flight speeds it is advisable to use the ramjet engine together with a uniflow or double flow turbo-jet engine. In this case the turbo-jet engine provides take-off, landing and flight at subsonic and moderate supersonic speeds. A bodily combination of ramjet and turbo-jet engine in a single combined air-breathing jet engine is also possible. Depending on the requirements it works either as a turbo-jet or a ramjet engine. This combined engine is usually called a turbo-ramjet engine.

For starting and accelerating flying vehicles with a ramjet engine up to the speed where the engine begins to operate effectively some other engine, specifically a rocket engine, can be used. Another possibility is a combination of the principles of working of these two types of engines into a single rocket-ramjet engine.

Depending on the speed of the flying vehicle for which the engine is designed a ramjet engine is classified as subsonic (shown in Fig. 40), supersonic or hypersonic.

The ramjet has not been widely used in aviation. In modern jet aviation the engine most used is the turbo-jet. However, any further increase in flight speeds toward hypersonic speeds will bring the temperature of the air leaving the compressor of a turbo-jet engine nearer to the maximum temperature of gas at the turbine inlet permissible from the point of view of reliability and long service. The equality of these temperatures, as already mentioned, inhibits the burning of the fuel in the combustion chamber located before the turbine. But in that case a turbo-jet engine without an afterburner could not work and develop thrust, while the working of a turbo-jet engine with an afterburner is possible only by utilizing the energy of the fuel burned in it.

During such an engine operation the compressor, turbine and combus-

tion chamber located between them do not help but hinder the creation of thrust, offering resistance to the air passing through the engine. If these components are removed notionally and the air from the diffuser is sent directly to the afterburner the efficiency of the engine operation will increase and in essence it will be converted into a ramjet engine.

Therefore as we approach hypersonic flight speeds the turbo-jet engine will probably have to cede its place in aviation to the ramjet or a combined turbo-ramjet engine.

Unlike a subsonic ramjet engine, the hypersonic engine must have a converging diffuser (air intake) and a diverging jet nozzle.

According to foreign literature, at flight speeds up to roughly 6–7 M ramjet engines with subsonic combustion have the higher efficiency while at higher flight speeds it is the one with supersonic combustion.

The first experimental research on ramjet engines was carried out in the Soviet Union in 1932–1935 under the guidance of Yu.A. Pobedonostsev.

In the early war years of 1939–1940 a ramjet engine of I.A. Merkulov's design was installed for the first time under the wings of the I–152 and I–153 of N.N. Polikarpov's design and used as a booster power plant for these aircraft (the main engine was a reciprocating engine), which made possible an increase in maximum speed of roughly 10–15%. The credit for building up the theory of ramjet engines goes to the scientists of our country.

Turbo-ramjet engine

A combined air-breathing engine uniting a uniflow or double flow turbo-jet engine and a ramjet engine is called as a turbo-ramjet engine. Depending on the requirement it can operate in the regime either of a turbo-jet or of a ramjet engine.

Such engines can be built on the basis of a uniflow turbo-jet engine with afterburner or a by-pass turbo-jet engine with forward fan and afterburner.

In the first case the turbo-ramjet engine differs from the basic one as shown in Fig. 35 by the presence of a system that enables air from the intake system to be directed not to the compressor, as usually happens in a turbo-jet engine, but directly to the afterburner, by-passing the compressor, main combustion chamber and turbine.

Thanks to this it is possible to use the combination of the intake system, afterburner and jet nozzle as a ramjet engine. Naturally, in this case the fuel is burned only in the afterburner. The turbine and the compressor do not operate.

In the second case the turbo-ramjet engine differs from the basic one by the presence of a device that enables all the air entering the engine to be directed into the secondary duct and use of this duct, the afterburner and

jet nozzle as a ramjet engine. The fuel in this case is burned only in the afterburner and the fan and turbine do not work. Their blades are feathered.

It is also possible in the second case to use the same system as in the first.

ROCKET ENGINES

A rocket is a reaction engine used for thrust buildup, energy source and working medium source installed on the vehicle to be propelled.

The main advantage of the rocket engine over the air-breathing jet engine is its ability to work and develop thrust at any speed and at any flight altitude. Rocket engine thrust remains constant during a change in flight velocity and is little affected by the altitude of the flight.

The rocket engine is usually used in aviation as an auxiliary engine for different types of aircraft. It is widely used in rocket technology and is the basic type of engine in modern cosmonautics.

At the present time heat rocket engines are used in aviation, rocket technology and cosmonautics, using the chemical energy of a liquid or solid propellant. In the first case the engine is called a liquid-propellant rocket engine, in the second a solid-propellant rocket engine.

Liquid-propellant rocket engine and solid-propellant rocket engine

The first ideas and schemes for liquid-propellant rocket engines were proposed in 1903 by the great Russian scientist and inventor K.E. Tsiolkovskii. The main element of the liquid-propellant rocket engine is the chamber, consisting of head *1* (Fig. 41), combustion chamber *2*, nozzle *3*, cooling jacket *4* and flame igniter (device for ignition) *5*.

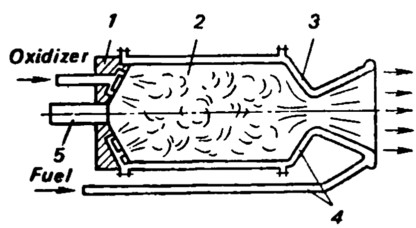


Fig. 41. Chamber of liquid-propellant rocket engine.

In the chamber there takes place combustion of the propellant being fed into it (with the aid of a pump or pressure feed system) from tanks and considerable part of the enthalpy of the combustion products is converted into kinetic energy.

During the expansion of the combustion products in the nozzle the pressure is lowered and the speed substantially increases. With gas velocity increase at the nozzle exit the economy of the engine improves. The greater the velocity and the mass of gas exiting from the nozzle per unit of

time the higher the thrust of the liquid-propellant rocket engine.

To obtain a high velocity of combustion products at the nozzle exit a propellant is required to possess large calorific value and a considerable effective pressure ratio in the nozzle. Therefore in the combustion chamber a fairly high pressure is maintained. For example, in the Soviet space engine RD–107 it is 60 atm. For this engine, flying since 1957, the gas velocity at the nozzle exit in flight reaches approximately 3 to 3·1 km/sec. The engine operates on a propellant consisting of liquid oxygen (oxidizer) and hydrocarbon fuel.

In liquid-propellant rocket engines we frequently use as commonplace a hydrocarbon fuel as kerosene. More effective is hydrogen, which in burning liberates almost three times the heat from the same quantity of kerosene by weight.

For engines that operate on a propellant consisting of liquid oxygen and liquid hydrogen the gas velocity at the nozzle exit in flight at a great distance from the earth reaches approximately 4.2 to 4.4 km/sec.

As for the aircraft gas turbine engine, for a liquid-propellant rocket engine during operation a flame igniter is not required. The flame in the combustion chamber created when starting the engine is maintained by a continuous feed of propellant components into the chamber. To light a flame for starting we use a pyrotechnic or electric flame igniter and other means.

Some liquid-propellant rocket engines, including some space engines, operate on a hypergolic propellant, i.e. on a propellant that ignites on contact between the oxidizer and fuel as a result of the chemical reaction developed by their interaction. In this case a flame igniter is not required.

Cooling of the engine chamber, necessary because of the high temperature of the combustion products (3,000°C and above), is usually achieved with the aid of one of the propellant components. It first cools the chamber walls from the outside and then enters the combustion chamber through the heat. Frequently the chamber walls cool not only from the outside but also from the inside. For this we lower the temperature of the layer of combustion products near the wall by some means or other. Some other methods of cooling the engine chamber are also used.

The liquid propellant rocket engines being used in cosmonautics have one, two or several chambers. For example, the Soviet space engine RD–107 has four main and two steering combustion chambers.

In the carrier rockets of space vehicles liquid-propellant rocket engines with a gas turbine pump drive are commonly used to feed the propellant into the engine chamber. The turbine together with the fuel pumps form the turbo-pump unit of the engine.

As the working medium for the turbine we usually use the gas or steam-gas developed in the gas generator or steam-gas generator in the

form of combustion products or decomposition products of the main or auxiliary rocket propellant. Steam-gas is the mixture of water vapors and oxygen obtained during the decomposition of hydrogen peroxide or a mixture of combustion products of the rocket propellant in the gas generator and water vapors injected into the combustion products to lower their temperature.

The Soviet space engines RD–107 and RD–119, for example, have a turbo-pump propellant feed system. In the RD–107 engine the supply of propellant to all chambers is achieved with the aid of one overall turbo-pump unit whose turbine is driven by steam-gas.

The liquid-propellant rocket engines utilized in manned spaceships should possess the greatest reliability, which is facilitated by the use of the simplest possible construction.

In such ships the use of a liquid-propellant rocket engine not with a turbo-pump propellant feed but with the simpler pressure feed, achieved by means of the creation of pressure in the fuel tanks exceeding the combustion chamber pressure, finds a place.

In order to avoid excessive weight of fuel tanks in a spaceship, which is a big deficiency in a pressure propellant feed with high pressure in the combustion chamber, a combination of this feed with low combustion chamber pressure is possible. For example, the liquid-propellant rocket engines of the *Apollo* spaceship have pressure propellant feed and operate at pressure in the fuel tanks approximately from 12 to 16 atm and combustion chamber pressure from 7 to 9 atm.

This low combustion chamber pressure on the ground and at low altitudes substantially lowers the efficiency and economy of engine operation.

However, at a considerable distance from the earth even at this pressure a sufficiently high effective pressure ratio is obtained in the nozzle for efficient and economical engine operation.

Unlike the liquid-propellant rocket engine, in the solid-propellant rocket engine all the propellant is placed in the combustion chamber, which simultaneously serves as a fuel tank. Therefore the solid propellant rocket engine does not need the propellant feed system from tanks to engine chamber that is essential for the operation of liquid-propellant rocket engines.

The main elements of solid-propellant rocket engines are the combustion chamber *1* (Fig. 42), the propellant charge *3* placed in it, nozzle *2* and igniter *4*.

The construction of a solid-propellant rocket engine and its maintenance during operation and storage are simpler than for liquid-propellant rocket engines. Its special advantage is constant readiness for operation and simplicity of starting. By comparison with the liquid-propellant rocket engine the solid propellant rocket engine makes possible a big reduction

in the time needed to prepare the rocket for starting. It allows storage of rockets charged with propellant and ready for launching for a long time and at the same time considerably lowers the cost.

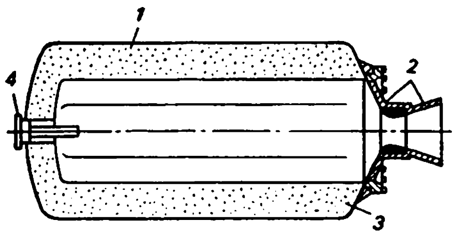


Fig. 42. Solid-propellant rocket engine.

The main disadvantages of the solid-propellant rocket engine are a lower specific thrust by comparison with the liquid-propellant rocket engine and also severe difficulties in control of the engine thrust valve. The specific thrust (or specific impulse) of a rocket engine using chemical propellant is the ratio of the thrust it develops to the weight propellant consumption per second.

Of great interest is the sectional solid-propellant rocket engine. It consists of parts (sections) separately manufactured, controlled and transported to the launching pad.

The front (nose) section is the front part of the combustion chamber of the engine, the rear (tail) section terminates with a jet nozzle, and the intermediate standard sections are interchangeable.

The engine can be assembled for the front, rear and a variable number of intermediate sections, which makes it possible in a simple way to change the total (sum) impulse of the engine and parameters of the flight vehicle within wide limits, for example the range or payload.

The total impulse of a solid-propellant rocket engine is the product of the average thrust (during the engine's operating time) it develops and the time of operation of the engine, corresponding to complete burn-up of the propellant charge.

Liquid-propellant rocket engines and solid-propellant rocket engines are able to develop very high thrust force with low weight and small overall size. Under terrestrial static conditions and especially in flight at altitudes over 10 to 20 km the specific weight of these engines is many times less than for a turbo-jet engine.

They have great advantages over the turbo-jet engine with respect to the thrust being developed in one unit, its invariability with change in flight speed, small change during climb and lightness and small size.

However, their service life is much shorter and the fuel economy at the speeds and altitudes of contemporary aviation is much worse than for a turbo-jet engine.

To date rocket engines have been little used in aviation as the main engine of an aircraft. It is possible that with an increase in the speed and altitude of flight rocket engines will play a more important role in aviation.

In the Soviet Union the liquid-propellant rocket engine was used for

the first time as the main engine of an aircraft more than 25 years ago on the BI aircraft designed by a team under the direction of chief designer V.F. Bolkhovitinov. The successful flight test of this aircraft was conducted in May, 1942, by pilot G.Ya. Bakhchivandzhi.

The powerful liquid-propellant rocket engines and solid-propellant rocket engines used in cosmonautics develop in one unit a much higher thrust than air-breathing jet engines. The thrust in the cavity of the RD-107 engine exceeded 100 tons.

Nowadays in cosmonautics for the launching and acceleration of space vehicles weighing many tons we use more powerful rocket engines burning solid or liquid propellant. Based on materials in the foreign press, the thrust of these engines in one unit reaches about 700 to 800 tons for a liquid-propellant rocket engine and 450 tons for a solid-propellant rocket engine. Solid-propellant rocket engines have been developed with a thrust of over 1,000 to 2,000 tons, designed for heavy transport space systems.

Hybrid rocket engine

In the hybrid rocket engine, also called the blended-propellant rocket engine, thrust is built up with the help of the chemical energy of a propellant whose components are in different states, for example solid fuel and liquid oxidizer.

Based on materials in the foreign press, experimental research on this engine has been going on in a number of countries since about 1955. Much experimental material has been accumulated and experimental models of engines with thrust up to 20 tons have been designed and tested.

The hybrid rocket engine is simpler and cheaper than the liquid-propellant rocket engine, its propellant economy is superior to the solid propellant rocket engine's, and the thrust value can be controlled within wide limits.

Nuclear rocket engine

One possible way to bring about a considerable reduction in the propellant and working medium consumption of heat rocket engines is the use not of the chemical energy of a propellant but of nuclear energy to preheat the working medium.

In heat rocket engines using a chemical propellant (they are frequently called thermochemical rocket engines) the propellant serves not only as the energy source but also as the source of the working medium. In these engines the propellant combustion products are used as the working medium. The situation would be different in a heat rocket engine using nuclear fuel. In it the fuel would serve only as the energy source, utilized to heat the working medium, for which a substance of low molecular weight, for example hydrogen, would be used.

The specific impulse of the heat rocket engine is largely determined by the ratio of the absolute temperature of the working medium (before the nozzle) to its molecular weight. The higher this ratio, the higher the specific impulse. Therefore the use of hydrogen, whose molecular weight is much less than the combustion products of a chemical rocket propellant, as the working medium would make it possible to obtain in the nuclear heat rocket engine a higher specific impulse even at a lower temperature of working medium.

In the nuclear engine shown in Fig. 43 the hydrogen from the tank is fed through the cooling jacket of the engine nozzle, with the aid of a pump driven by a gas turbine, to the nuclear reactor, where it is heated to a high temperature. From the reactor the heated gaseous hydrogen enters the nozzle. From here it enters the surrounding medium at very high velocity, creating thrust. Part of the gases from the nozzle is diverted to drive the turbine. The gases exiting from the turbine are used to create low supplementary thrust.

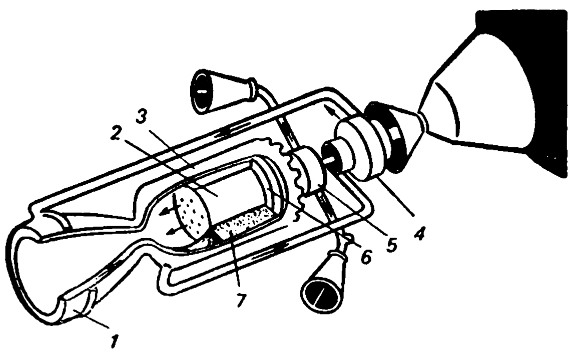


Fig. 43. Nuclear heat rocket engine:

1—nozzle; 2—active region of nuclear reactor; 3—power shell; 4—pump; 5—gas turbine; 6—shield; 7—neutron reflector.

Based on materials in the foreign press, bench tests of reactors and an experimental nuclear engine with a thrust of about 25 tons make it possible to expect for the flight model of the nuclear engine approximately double the specific impulse of contemporary thermochemical rocket engines.

The use of a nuclear engine instead of a thermochemical one in the top stage of the carrier rockets of heavy space vehicles could prove very advantageous. It would make it possible to increase the payload substantially and also to perform space flights whose accomplishment is prevented by the inadequate specific impulse of thermochemical engines. The nuclear engine could be successfully used in rocket-space systems for flights bet-

ween the earth and the moon and between the earth and other planets of the solar system.

Based on materials in the foreign press, a flight model of a nuclear rocket engine with a thrust of about 34 tons, weighing 8.2 tons and having an exhaust velocity of working medium from the engine into the surrounding medium of 8.1 km/sec, will be ready for flight tests in the second half of the 70s.

A variation of the thermal nuclear engine is the radioisotope engine. There is no reactor and the preheating of the working medium is achieved with heat generated by nuclear energy released with the decay of a radioactive isotope. The latter is used as the propellant.

In terms of specific impulse the radioisotope engine and engines with nuclear reactors are close to each other. The thrust of the radioisotope engine is low but the endurance of operation is much greater than for thermochemical rocket engines.

Based on materials in the foreign press, the thrust of radioisotope engines being developed does not exceed several kilograms but the duration of operation can reach 30 days.

Nuclear energy can be used for heating the working medium not only rockets but also of jet engines. According to materials published in the press, the use of nuclear instead of chemical energy to heat the working medium of air-breathing jet engines would be advantageous on aircraft with high take-off weight (about 450 tons and up) and with long range or duration of flight. On such aircraft a nuclear power plant could be installed with a reactor designed to work without refueling for 1,000 hours and more and radiation shielding necessary for the safety of the crew, passengers and ground maintenance personnel. These aircraft would possess great carrying capacity and the range and duration of flight could be many times greater than for aircraft with the same take-off weight but with engines using chemical propellant.

Electrical rocket engine

Great economy in the consumption of propellant and working medium in rocket engines can be achieved by using electrical energy for thrust buildup.

In an electrothermal rocket engine the electrical energy is converted into heat which heats the working medium of the engine. The heated working medium flows out of the engine through the jet nozzle into the surrounding medium at high velocity, creating thrust.

The basic elements of this engine are a device for preheating the working medium and the jet nozzle, in which the thermodynamic acceleration of the working medium is achieved.

Various methods of heating the working medium used are: contact (Fig. 44) and heating with the aid of an electric arc (Fig. 45), etc.

As working medium in the electrothermal engine we usually use hydrogen or ammonia, which is less effective but more convenient to store.

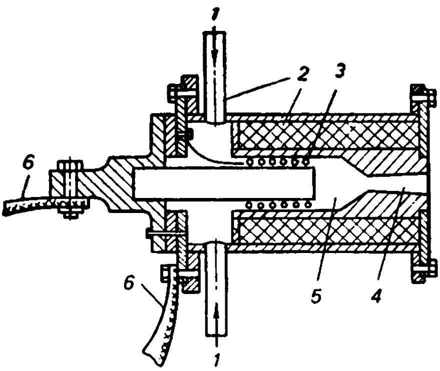


Fig. 44. Electrothermal rocket engine with contact heating of the working medium:

1—inlet of working medium; 2—insulator; 3—heating resistance; 4—nozzle; 5—damping chamber; 6—electric power supply.

Besides the electrothermal engine, electrorocket engines also include electrostatic and electromagnetic (electrodynamic) engines.

In the first the electrical energy applied to the engine is converted into the kinetic energy of the flow of charged particles. The particles of the working medium, which carry an identical (usually positive) electric charge, are subjected to the accelerating power effect on an electrostatic field. These particles can be ions charged by colloidal particles or even specks or drops. The reciprocal power effect exerted by the accelerating particles of the working medium on the electrodes, which create a field, is the thrust of the electrostatic rocket engine.

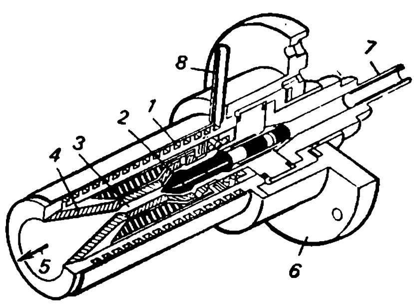


Fig. 45. Electric arc rocket, regeneratively cooled engine:

1—cooled housing; 2—cathode; 3—arc chamber; 4—nozzle; 5—exit of gas; 6—mounting flange; 7—inlet of working medium, which cools the engine; 8—main inlet of working medium.

Depending on precisely which charged particles (ions or colloidal particles) are accelerated in the electrostatic field, the engine is called ion or colloid.

The flow of charged particles after acceleration should be neutralized before leaving the engine into the surrounding medium. Indeed, if the flight vehicle in which the engine is installed left behind particles with like (usually positive) charges, then it would quickly acquire a considerable charge of the opposite sign and begin to attract the charged particles being emitted by the engine. As a result the engine thrust would decrease or completely disappear. For neutralization of the flow of positively charged particles we usually use electrons.

Based on materials in the foreign press, at the present time among electrostatic rocket engines the ion engine is the most developed and tested in space flight. In it positively charged particles are obtained by ionization of the working medium. In this case from each atom of the working medium we separate one of its electrons, thereby converting a neutral atom into a positively charged ion. The ions obtained in this way are accelerated in the electrostatic field to build up thrust. Before exiting from the engine the ion flow is neutralized by the addition of electrons.

As a working medium in the ion engine we use a substance with comparatively high atomic weight and low expenditure of energy for ionization. The high atomic weight of the working medium makes it possible to obtain high thrust with the dimensions and weight of the ion engine. We usually use cesium with an atomic weight of 133 and low expenditures of energy for ionization or mercury possessing an even higher atomic weight (200) and with the added advantage of simpler storage.

The ion engines built abroad are distinguished not only by their working medium but also by the method of ionization. In an engine with contact ionization the ions are obtained by the contact of atoms of the working medium (usually cesium vapor) with the hot surface of some metal, for example tungsten. In an engine with electron bombardment (Fig. 46) the ions are obtained as a result of collisions of atoms of the working medium (cesium or mercury) with electrons being emitted by the heated cathode. In order to increase the number of collisions and thereby the number of ions obtained, the path of electrons from the cathode to the anode is artificially lengthened with the aid of a weak axial magnetic field.

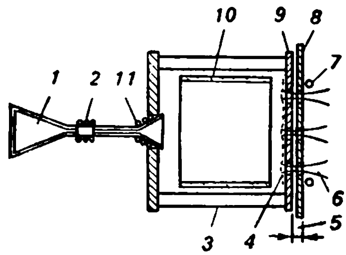


Fig. 46. Cesium ion-rocket engine with electron bombardment:

1—volume with cesium; 2—evaporator and flow regulator of cesium; 3—permanent magnet (cylindrical shell); 4—layer of plasma; 5—ion acceleration section; 6—beam of emerging ions and electrons; 7—neutralizer; 8—accelerating electrode; 9—screen grid; 10—anode (cylindrical shell); 11—autocathode.

In an electromagnetic rocket engine the electrical energy supplied to the engine is converted into the kinetic energy of the plasma jet being ejected from the engine into the surrounding medium. For an electromagnetic engine the acceleration of the working medium is achieved with the aid of a magnetic field. However, the latter can have a powerful influence on the substance only if this has an electric current flowing through it. Ordinary neutral gas is not a conductor. Therefore the gaseous working medium of the electromagnetic engine is ionized and converted into the plasma state.

With the passage of electric current through the working medium it is subjected to the accelerating power effect of the magnetic field.

In the electromagnetic rocket engine we usually use hydrogen, argon, nitrogen or helium as the working medium. Since in this engine the working medium accelerated with the aid of a magnetic field is in the state of plasma it is often called a magneto-plasma-dynamic or plasma electric rocket engine.

The use of electrical energy for the creation of thrust in electrostatic and electromagnetic rocket engines makes it possible to accelerate the working medium to speeds considerably exceeding those attainable in heat rocket engines. In the ion and plasma engines constructed abroad the exhaust velocity of the working medium from the engine and accordingly the specific thrust (specific impulse) achieved are approximately 10–30 times greater than in contemporary liquid-propellant rocket engines.

The main disadvantage of these engines as compared to liquid-propellant rocket engines is the much greater specific weight of the power plant, including the engine itself, the source of the electrical energy used by the engine and in a number of cases also the converter of the electrical energy of the source in accordance with the current and voltage required for engine operation.

The large specific weight of a power plant with an electric rocket engine is the reason for the fact that these engines are not capable of even lifting themselves from the earth, much less of providing take-off for extraterrestrial flight vehicles.

However, the considerable specific impulse of such engines and the economy in the consumption of working medium connected with it makes their use in cosmonautics for various missions under conditions of prolonged flight not only possible but even highly advisable.

Electric rocket engines are low-thrust engines (being calculated not in tons, as in many thermochemical rocket engines, but most frequently in grams) and engines of long service life, necessary for the successful application of these engines in cosmonautics. The service life of electric rocket engines attains several thousand hours. In the foreign press the view has been expressed that the service life of some of these engines may be brought to 20,000 hours and more.

Electric rocket engines can be used on space vehicles primarily as auxiliary engines and subsequently as main engines (sustainer).

In December, 1964, for the first time under conditions of space flight the successful testing of six plasma engines fitted to the sides of the Soviet automatic station *Zond-2* was conducted. These engines were utilized as controls for the orientation system used to maintain the altitude of the station relative to the sun.

Electric rocket engines have great prospects for use in space vehicles

under conditions of prolonged interplanetary flight. The low consumption of working medium in these engines makes it possible to increase considerably the payload weight of systems for flight between the earth and other planets of the solar system.

Electrical energy can be used for the creation of thrust not only for rocket engines but also for reaction engines using as their working medium a substance gathered from the surrounding medium. This substance, for example, can be the nitrogen forming part of atmospheric air. Electric reaction engines of this type can be used for flights in the upper atmospheric layers.

In October, 1969, a report was published in the press about a number of experiments conducted by Soviet scientists in the earth's ionosphere with the aid of *Yantar* automatic flight vehicles. During these experiments the electric reaction engines of the *Yantar* vehicles used atmospheric nitrogen for the creation of thrust and operated quite stably.

In October, 1970, a report was published about the work of the Soviet scientists G.L. Grodzovskiy, Yu.I. Danilov, N.F. Kravtsev, M.Ya. Marov, V.Ye. Nikitin and V.V. Utkin on the creation of an electric air jet engine. The engine they developed was capable of using any gases of the earth's atmosphere as the working medium. It was successfully tested under conditions of ionospheric flight. The experiments conducted demonstrated the possibility of using electric reaction engines which operated on atmospheric air or nitrogen for flights in the upper atmosphere of the earth at altitudes exceeding 100 kilometers.

Thanks to the work of the Soviet scientists there appeared a real prospect of creation of orbital flight vehicles capable of accomplishing lengthy flights in the ionosphere around the earth due to the use of gases of the ionosphere as the engine's working medium.

COMBINED AIR-BREATHING ENGINES

Engines of this type are not yet widely used on flying vehicles because in the range of flight speeds and altitudes of modern jet aviation the air-breathing engines now used possess better economy and have a correspondingly lower specific fuel consumption than that of a combined air-breathing rocket engine. However, as reported in foreign literature, in future aviation with its much larger range of flight speeds and altitudes it is possible that air-breathing rocket engines will find their use.

A combined air-breathing rocket engine is a jet engine using both atmospheric air and rocket fuel as its working medium or source for it.

Air-breathing rocket engines have in themselves the typical peculiarities of air-breathing jet engines and rocket engines. They usually have two combustion chambers, in one of which oxygen from the atmospheric air

serves as an oxidizer, while in the other the oxidizer carried along with the engine on the flying vehicle is used. The best known engines of this class are turbo-rocket and ramjet-rocket engines.

The basic components of a ramjet-rocket engine are the intake system through which atmospheric air enters the engine, two combustion chambers (combustion chambers for rocket fuel and afterburner) and jet nozzle.

In the first combustion chamber rocket fuel containing less oxidizer than that necessary for complete combustion of the fuel is delivered and burned. The gases formed in the first chamber emerge and enter the second chamber (afterburner).

Here the combustible part of these gases not burned in the first combustion chamber due to the lack of oxidizer are burned along with an additional injection of fuel. The oxygen in the atmospheric air entering the afterburner through the intake system is used as the oxidizer. The gases from the afterburner enter the jet nozzle from which they are released at high velocity into the surrounding medium, creating thrust.

The advantage of a ramjet-rocket engine over a ramjet is its ability to operate and develop useful thrust under static conditions and at low flight speeds.

A turbo-rocket engine differs from a ramjet-rocket engine by the presence of a low-pressure compressor and a gas turbine which drives it. The gases entering the combustion chamber of the rocket and fuel entering the gas turbine serve as the working medium. After leaving the turbine they are led to the afterburner. Here they mix with the air first compressed in the intake system and later in the low-pressure compressor.

In construction a turbo-rocket engine is more complicated than a ramjet-rocket engine. Nevertheless it has higher efficiency under static conditions and also at subsonic and moderately supersonic flight speeds.

According to its technical data and characteristics, the turbo-rocket engine occupies an intermediate position between turbo-jet and liquid-propelled rocket engines. For example, the specific fuel consumption of a turbo-rocket engine is more than that of a turbo-jet engine but less than that of a liquid-propelled rocket engine, while the reverse is true of its specific weight.

The smaller specific weight and less marked reduction in thrust of the turbo-rocket engine during climb allow it to be used at higher altitudes than those at which a turbo-jet engine can be used.

It is undoubtedly worth comparing combined air-breathing rocket (turbo-rocket and ramjet-rocket) engines with combined air-breathing (turbo-ramjet) engines.

According to foreign literature it is the turbo-ramjet engine that possesses the maximum economy and correspondingly minimum specific fuel consumption at subsonic and moderate flight speeds. It is however the

heavier engine (by specific weight) and during climb its thrust falls more sharply than that of the two other engines.

At high supersonic speeds, approaching hypersonic, all three engines come noticeably closer to one another in specific fuel consumption.

Both turbo-ramjet and air-breathing rocket engines can be used on vehicles with large supersonic and hypersonic flight speeds. The future will show which of these engines will find practical application on hypersonic flying vehicles.

SECTION FOUR

Aircraft Equipment

CLASSIFICATION

If one takes a glance at the cockpit (Fig. 47) one is amazed by the multiplicity of measuring instruments, handles, buttons, instructions for switching on and setting in motion different mechanisms, instruments, apparatus and devices for controlling flight and regimes of engine operations, all contributing to high reliability, flight safety and the best fulfillment of the assignment.

All technical devices located on the aircraft are known as airborne equipment.

Depending on the type of aircraft and its task the volume of aircraft equipment can be diverse but its basic aspects remain the same.

Aircraft equipment can be classified according to various features: according to the energy used (electrical, pneumatic, hydraulic, and so on); according to the purpose of different aggregates and devices (landing, navigation, illumination, and so on) and a number of other equally important features. But no matter how we have classified them, no matter how we have arranged the aircraft system "on the shelves" it will always seem that a particular device could have been equally well included in one classification as in another.

It is quite clear that the equipment of a modern aircraft is not a simple collection of devices. It is a complex of functionally interconnected instruments and devices such that the normal operation of one is sometimes impossible without the help of another.

In classification the groups of electrical and radio equipment are almost always separated out. In the first group there are two basic subgroups: the sources and the consumers of electrical energy. But is not any

radio device a consumer of electrical energy? Doesn't the radio transmitter, for example, consume electrical energy? This means a radio transmitter should formally be included in the first group.

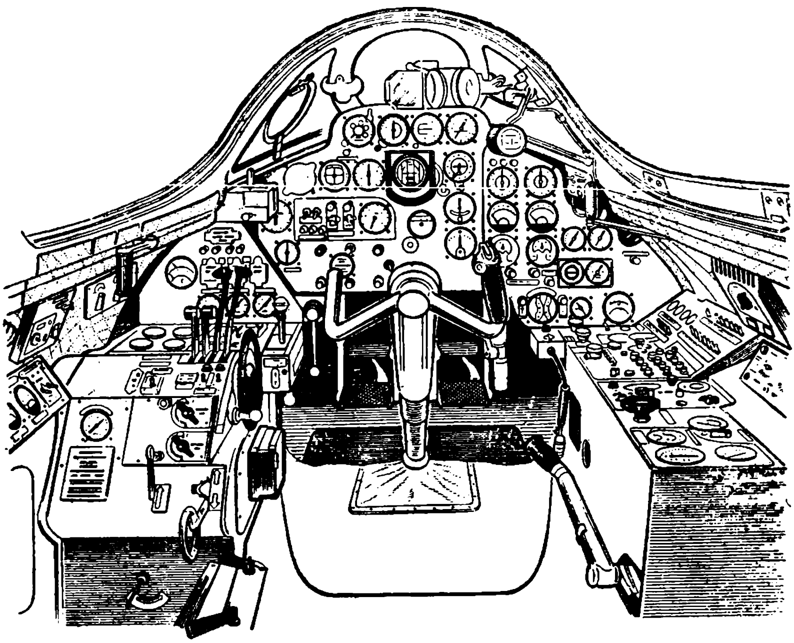


Fig. 47. General view of a cockpit.

However, this is not done because all radio devices have common physical principles of work involving reception and transmission of electro-magnetic waves. At the same time it once more indicates some kind of convention whereby practically any classification can be given to specific aircraft instruments and devices.

But it is possible to choose a number of typical features according to which aircraft equipment is subdivided into some large groups. According to most standard schemes the classification of aircraft equipment consists of five groups:

instrumentation equipment;
electrical equipment;
radio equipment;
automatic equipment; and
vital systems.

Sometimes more groups are added, such as the group of special equipment. This usually identifies the basic purpose of the given aircraft. Thus on a reconnaissance aircraft aero-photo and cine cameras are mounted to enable it to carry out topographical photography of the ground. Aircraft

helping agriculture have various installations for fertilization and pollination, pest control and so on in addition to the usual equipment.

We will give a brief description of the groups of aircraft equipment mentioned above.

Instrumentation is designed to furnish the pilot with information about the parameters of the aircraft's motion (speed, altitude, course and so on), about the regimes of engine operation, about the position of various mechanisms (undercarriage, flaps, etc.) and also about emergency situations (fire, sudden depressurization of cabin). In conformity with this the instrumentation equipment is subdivided into three subgroups: flight navigation instruments, engine operation-control instruments, auxiliary pick-ups and signaling devices of various regimes.

The electrical equipment generates electrical energy, supplies it and distributes it among the various types of airborne electrical devices and ensures their normal operation during flight. Electrical equipment is subdivided into the sources of electrical energy (accumulators, generators and converters), electrical switch gears (aircraft wiring, contactors, relay, etc.) and the consumers of electrical energy (electric motors and other devices).

Radio equipment is intended to maintain two-way communications with ground control and guidance towers, air-to-air and internal communication and radio-navigation for landing under difficult meteorological conditions and for pinpoint bombing, firing and other battle operations in zero visibility. The radio equipment includes radio receivers and transmitters and radio-navigation devices, radar sets and target finders, radio engineering instruments for all-weather landing, radio systems for location and identification and others.

Automatic equipment ensures automatic control of the flight and operational regimes of the engines (without the crew's intervention). The aggregates of the aircraft automatic equipment are essentially cybernetic systems using analog or digital computers. This group includes autopilots, autonavigators, aircraft computers and others.

The vital systems create for the passengers and crew the normal physiological conditions essential for vital activities at high altitudes, during sudden depressurization of the cabin, while abandoning the aircraft in distress and in case of landing in regions (desert, ocean, etc.) difficult of access. This group of aircraft equipment includes airborne and parachute oxygen devices, plants for air ventilation and airconditioning in the cabins, pressure suits, diver's suits, ejector seats with protection shutters (screens), parachute systems (single- and multi-cascade), means of staying afloat (life jackets, boats, rafts) and food stocks.

For passenger amenities and comfort domestic equipment (electric kitchenware, devices for storing food products and drinking water, aircraft drug store, sliding tables, adjustable ventilators) is provided.

Armament is part of the equipment of the front line and trainer aircraft of military aviation. This includes bombing and common machine-gun units, "air-to-air" and "air-to-surface" missiles and so on.

THE FLIGHT-NAVIGATION INSTRUMENTS

The flight-navigation instruments are used in the control systems of aircraft (for piloting and flying of aircraft). The pilot as well as the navigator makes use of readings of these instruments.

Altimeter

An instrument for measuring height is called an altimeter. Determination of height by barometric pressure up to a height of 30–35 km is one of the most commonly used methods enjoying widespread application in flying machines.

This method is based on measuring the (absolute) atmospheric pressure which, as is well known, decreases as height increases. At any moment of time the atmospheric pressure corresponds exactly to the height (Fig. 48). Therefore the height of an aircraft can be determined by measuring the atmospheric pressure.

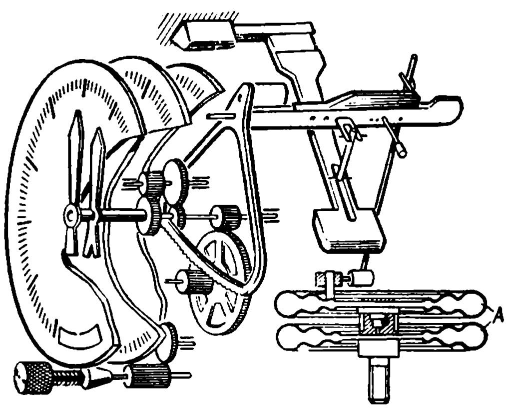


Fig. 48. Altimeter.

A corrugated diaphragm made of byrillium bronze with a soldered entrance orifice, which is what an aneroid barometer is, senses the pressure of the surrounding air. It is an instrument very simple in use and application.

In fulfilling its function it does not transmit any signals, it does not need any radio communication with the ground, it is completely automatic and all information regarding flight altitude is directly taken from the surrounding atmosphere. For this purpose the so-called RAP–recorder of

atmospheric pressure is used (Fig. 49). In high-speed aircraft it is installed some distance away from places where fierce air disturbances occur. The RAP tube has special orifices and spiral rubber tubes through which the atmospheric pressure enters the altimeter case. The greater the height the

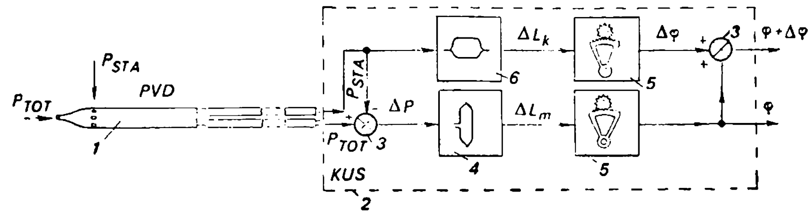


Fig. 49. Pick-up of air pressures:
1—metallic tube; 2—instrument casing; 3—adder; 4—membrane; 5—gears; 6—aneroid.

airplane reaches, the thinner the surrounding atmosphere. Consequently the pressure exerted on the aneroid barometer decreases. The aneroid box expands and with the help of levers and other elements of a kinematic mechanism moves a hand on the face of an indicator-dial. In some way the pilot receives information about an increase in altitude.

Speed indicator

Another important source of information for piloting an aircraft is the speed indicator.

The speed of an aircraft can be determined with reference to the airflow and also to the ground. The first is called airspeed *V*, the latter ground speed *W*. Obviously, if there were no motion of the air mass (wind) the two velocities would be identical in magnitude.

The principle of a speed indicator is shown in Fig. 50. The greater the speed of the aircraft, the greater the pressure of the airflow encountered; the diaphragm is expanded further and the angular deflection of the broad hand showing the "instrument-indicated" airspeed increases.

The instrument-indicated velocity is proportional to the pressure variation Δp which in turn is equivalent to the difference in dynamic pressure (pressure gradient of speed) and static pressure (atmospheric pressure). As Fig. 49 shows, information about these pressures is obtained from the atmosphere with the help of the RAP tube.

Each type of aircraft has a certain minimum lift component at which stability and maneuverability are maintained. At a constant angle of attack at flights below the speed of sound the lift component is directly proportional to the pressure gradient of speed. Consequently if the safe flight speed is kept constant according to instrument indications stability and maneuverability will always be ensured at any height the airplane is

flown. This explains why it is so essential for the pilot to know the meaning of instrument-indicated airspeed.

a)

b)

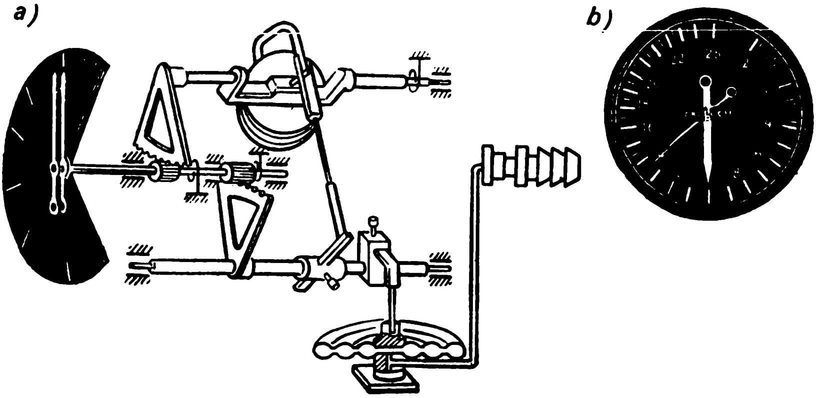


Fig. 50. Combined speed indicater:
a—kinematic mechanism; b—scale.

While solving problems like determining ground speed and drift angle from wind specifications, calculating and plotting the course, checking the track made good, etc. the pilot needs information about the true airspeed. For this purpose there is a second (thin) pointer on the instrument-dial.

The true airspeed corresponds to the flight speed with reference to the air and does not depend on the altitude, whereas the instrument-indicated speed depends on the height, because with increasing height the speed gradient diminishes. The two pointers of the instrument coincide only in sea-level flight.

With increasing height the thin pointer (true airspeed) moves somewhat ahead of the broad pointer (instrument-indicated airspeed). Why does this happen?

Fig. 50 shows that the deflection of the pressure-gauge box measuring the magnitude of the speed gradient is transmitted to both pointers of the indicator; as a result, they move at the same angle proportional to the magnitude of the instrument-indicated speed.

In order to obtain the true airspeed, a correction for air density and temperature has to be made. The dial for instrument-indicated speed is, however, calibrated on the assumption that outside atmospheric pressure and temperature remain constant ($p_{st} = 760$ mm mercury column, $t = +15°C$).

The correction is carried out automatically with the help of an aneroid barometer corrector. This aneroid barometer is a kind of miniature barometric altimeter. In the case of decreasing static pressure the aneroid

barometer expands and the thin pointer moves through the additional angle $\Delta\varphi$ on the dial (Fig. 49).

Temperature correction is carried out in the following way: It is usually assumed that the temperature of the surrounding air changes with increasing height according to the so-called international standard atmosphere. Thus for any pressure p_{st} there is a certain corresponding temperature. According to this, for temperature correction it is not necessary to equip the aircraft with a thermometer indicating the outside temperature. The aneroid barometer corrector is used for this purpose. It may be geared in such a way that its deflection ΔL_k will not only depend on static pressure but also on temperature, i.e. the deflection ΔL_k will be a function of p_{st} as well as of temperature.

Mach indicator

On the instrument panel there is another instrument called the Mach indicator.

At low subsonic speeds the aerodynamic characteristics of an aircraft depend on the velocity head of air and the magnitude of indicated airspeed determines the most favorable flight regime.

As the flight speed approaches the speed of sound the aerodynamic characteristics begin to depend essentially on the Mach number. Therefore at transonic flight speeds it is necessary for the pilot to have information not only on the true airspeed but also on the ratio of this speed to the speed of sound, i.e. the Mach number.

The wave drag at various altitudes comes into the picture at different speeds but at one and the same Mach number. This is very important because with the help of the Mach indicator the pilot knows that the aircraft has entered the zone of increased drag where aircraft controllability changes steeply.

Vertical speed indicator

The vertical speed indicator is a device which measures the vertical speed of an aircraft while ascending or descending. The instrument is of great importance for flying in the absence of visual ground contact.

The information it provides about the vertical velocity is necessary to enable the pilot to hold the aircraft at a safe rate of climb or descent, especially during the final approach. Apart from this, the vertical speed indicator is a useful device for controlling the maintenance of an assigned height ("echelon") during en route flights, and also for correctly determining the moment of transition from a dive into level flight.

The principle of the vertical speed indicator is based on measuring the changes in atmospheric pressure which occur with any change of height inside and outside the case of the instrument, which is connected with the

atmosphere by a capillary tube (Fig. 51). The difference in pressure is measured with the help of a pressure-gauge box placed inside the instrument case. The internal cave of the pressure-gauge box is directly connected with the atmosphere by a static tube similar to the one used in the atmospheric pressure recorder. During a change in height the pressure inside the instrument case connected with the atmosphere by a capillary tube lags behind the change in atmospheric pressure because the air is passing through the capillary tube at a relatively low rate. The magnitude of lag corresponds to the magnitude of the plane's vertical speed. As a result of this the changing pressure acts on the pressure-gauge box, causing it to expand or contract. These deflections are transmitted with the help of a kinematic mechanism from the center of the pressure-gauge box to the pointer of the instrument, indicating the magnitude of ascending or descending speed.

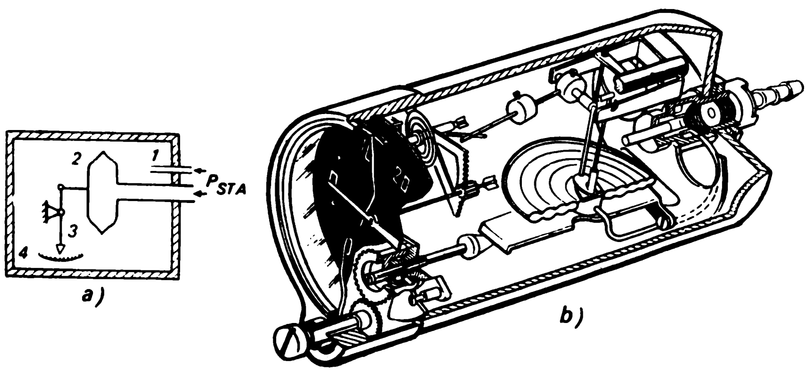


Fig. 51. Vertical speed indicator:

a—principle scheme; b—construction of the instrument.

Concept of gyroscopic instruments

It is quite difficult to even imagine instrumentation without gyroscopic instruments, i.e. artificial horizon, azimuth gyroscope, bank indicator. The gyroscopic instruments help the pilot to hold a given course accurately, to determine the specific location of the aircraft and to perform acrobatic maneuvers beyond the visual range of the earth and even of the stars.

The basis of every gyroscopic pick-up of flight information is a gyroscope. In engineering the gyroscope is a symmetrical, fast rotating body whose axis of rotation is free to turn in space.

A gyroscope is a rapidly rotating massive body *1* (Fig. 52) called a rotor. The axis of the rotor is mounted in the inner frame *2*, which is free to turn about its own axis. The axis of the internal frame is fixed in the

outer frame *3*. The outer frame in its turn can swivel about its own axis. Consequently, such a gyroscope has three axes of rotation and is called a gyroscope with three degrees of freedom (free gyroscope).

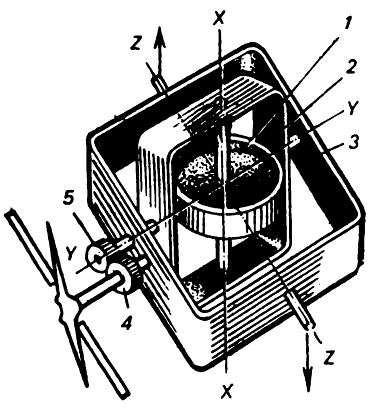


Fig. 52. Artificial horizon:
1—rotor; 2—inner frame; 3—outer frame; 4, 5—pinions.

The basic property of a free gyroscope is that at any position of the gyroscope the axis of its rotor maintains its direction in space unchanged.

It is interesting to note that unless the rotor of the gyroscope is set in motion at high speed the gyroscope shows no peculiar properties and behaves like any non-rotating body. For instance, if we turn the gyroscope mounting the axis of the rotor will start turning correspondingly. But as soon as the gyroscope rotor is set in motion at high speed the properties of the gyroscope abruptly change.

If the gyroscope mounting is turned the axis of the rotor maintains its direction in space and no longer turns with the mounting. Now if the axis of the rotor is directed toward a certain star in the heavens then its position with respect to the star will not change with time or any attitude adopted by the aircraft. This property of a gyroscope is widely used in modern navigation instruments.

It is necessary to understand that the axis of a gyroscope rotor maintains its position unchanged with respect to the stars (more accurately, with starry or so called "inertial" space) and not with respect to the surface of the earth. This property, as we will see later on, is of great importance.

Artificial horizon

The artificial horizon is used for determining the aircraft's position in space with respect to the skyline and for determining pitching and banking angles.

The angle of pitching (or pitch angle) is the angle between the longitudinal axis of the aircraft and the horizon; the angle of banking is the angle between the lateral axis of the aircraft and the horizon.

The working of an artificial horizon is based on the principle of using the basic property of the gyroscope which maintains the direction of the main axis in space irrespective of the aircraft's attitude.

In the artificial horizon the axis of rotation of the rotor is situated vertically and that of the casing and the outer frame horizontally (Fig. 52).

On the front of the instrument (Fig. 53) there is a movable horizontal

line representing the skyline. The aircraft silhouette represents the aircraft as if flying away from the observer. The position of the aircraft silhouette with respect to the horizontal line on the front of the instrument corresponds to the actual position of the aircraft with respect to the earth's horizon.

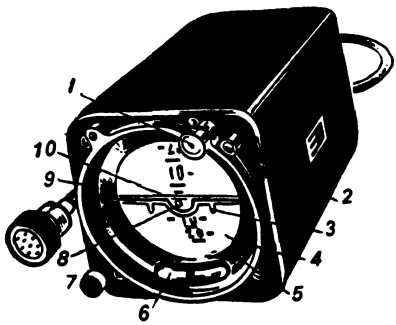


Fig. 53. Exterior view of artificial horizon:

1—locking knob; 2—supply and locking indicator lamp; 3—aircraft silhouette; 4—compass card; 5—scale of bank; 6—inclinometer; 7—pitching alignment set knob; 8—aircraft silhouette zero index; 9—pitching alignment index; 10—skyline.

In this instrument the main axis of the gyroscope must always maintain the vertical position. Together with the main axis of the gyroscope the inner frame also tries to hold the vertical position. The aircraft silhouette is connected to the outer frame and at the same time through two gear pinions with the inner ones.

If the pilot puts the aircraft into a turn the lateral axis of the aircraft is inclined. The axis of the outer casing of the artificial horizon is situated parallel to the lateral axis of the aircraft. Due to this, during a bank the casing of the artificial horizon and the axis of the outer frame of the gyroscope are also inclined along with the aircraft. The inner frame of the gyroscope holds its vertical position unchanged while the inner frame is turned. Meantime the driven pinion rolls around the stationary driving one. Together with the driven pinion the aircraft silhouette fixed to it also turns. Due to the transmission through two pinions the aircraft silhouette is turned in the same direction as the aircraft itself.

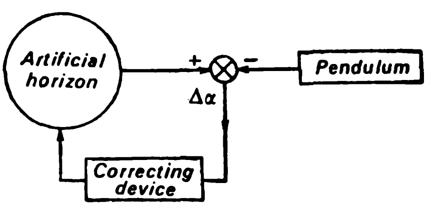


Fig. 54. Working scheme of correction of artificial horizon ($\Delta\alpha$—the angle of inclination of the gyroscope axis with the local vertical).

The axis of the rotor of the artificial horizon cannot remain vertical to the surface of the earth for a long time (let us remember that the axis of a gyroscope rotor holds the same orientation with respect to the stars). The rotation of the globe and also the aircraft's movement from one point of the globe to another lead to a situation where the axis of the rotor ceases to be vertical. Therefore the gyroscope axis needs constant correction, which is usually done by a pendulum "sensing" the vertical plane (Fig.

54). Almost all modern gyroscopic artificial horizons have pendulum correction.

Turn indicator

The turn indicator determines the direction and magnitude of the angular velocity of a turn undertaken by the aircraft about the vertical axis. Together with a slip indicator the turn indicator makes it possible to execute a correct turn (with zero slip).

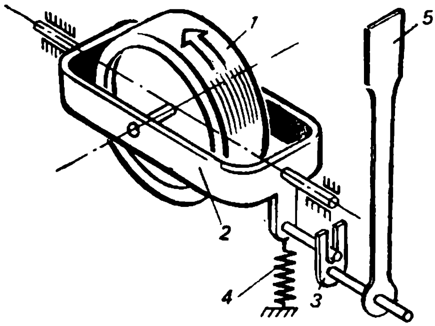


Fig. 55. Turn indicator:

1—rotor of the gyroscope; 2—frame; 3—plug; 4—spring; 5—pointer.

The principle of operation of a turn indicator is based on exploitation of the properties of a gyroscope of two degrees of freedom. This gyroscope is a gyroscope of three degrees of freedom with its outer frame artificially fixed. One of the degrees of freedom of the gyroscope is lost (hence the name: gyroscope of two degrees of freedom).

The basic parts of a turn indicator are a gyroscope with two degrees of freedom and a counteracting spring (Fig. 55).

If the aircraft turns about a vertical axis, for instance in an anticlockwise direction, then the casing of the instrument also turns along with the aircraft. The axis of the rotor meantime tries to coincide with the axis of forced rotation along the shortest path. Thus the left end of the rotor axis is raised, as a result of which the pointer of the turn indicator inclines leftward and indicates that the aircraft is executing a turn to port.

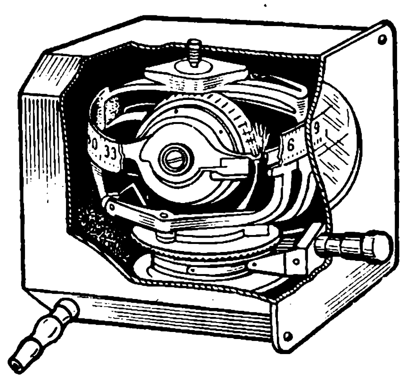


Fig. 56. Directional gyro.

Gyrocompass

The instrument that enables the pilot to hold a given flight course and also to execute turns of a given angle is called a gyrocompass.

Like the artificial horizon the gyrocompass uses the basic property of a gyroscope of three degrees of freedom, which retains the same position of the rotor axis in space. Therefore in construction these instruments are very similar to one another. The difference is that in the arti-

ficial horizon the axis of the gyroscope rotor is situated vertically while in the gyrocompass it is horizontal.

The gyrocompass shown in Fig. 56 is usually called a gyro directional indicator or directional gyro. It is so named because there is no directive force in the instrument that could set and constantly hold the gyroscope rotor in the direction of a magnetic or geographical meridian. Therefore the pilot pre-sets the compass card (a movable scale indicating the countries of the world) of the directional gyro in the required position (for example, for the given course of flight) and subsequently holds this direction for a short length of time.

It is impossible to fly long distances using bearings of a directional gyro. Due to the rotation of the globe, the movement of the aircraft and certain other factors the axis of the rotor of a directional gyro ceases to be horizontal and "deviates" from the given direction just as that of an artificial horizon deviates.

Usually the pilot observes the bearings of the directional gyro and corrects them from time to time. During this he is "turned" to the bearings given by the magnetic compass. Correction can also be done automatically, i.e. the magnetic compass automatically corrects the bearings of the directional gyro without the pilot's intervention (Fig. 57). A similar combined course (directional) instrument called a gyromagnetic compass contains in itself the qualities of both magnetic compass (high sensitivity, presence of directive force can determine the local meridian) and directional gyro (high stability against vibrations, overloadings and other undesirable mechanical factors).

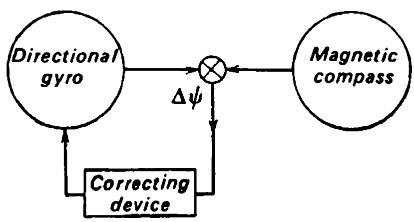


Fig. 57. Scheme of operation of corrections to directional gyro ($\Delta\psi$—is the angle of inclination of the gyroscope axis with the magnetic needle).

AIRCRAFT ENGINE INSTRUMENTS

These instruments enable the pilot to obtain continuous information about the operation of the aircraft's power plant.

The tachometer is an instrument designed to determine the angular velocity of rotation of the turbine shaft. On aircraft with reciprocating engines the tachometer measures the rotational speed of the crankshaft. The tachometer reading makes it possible for the pilot to judge the power or thrust developed by the engine.

Thermometers are used for measuring temperatures of working liquids and gases. For instance, the exhaust gas thermometer measures the

temperature in the nozzle of a turbo-jet engine. Other thermometers are also installed on an aircraft. They measure the temperature of the oil cooling internal parts of the engine, the temperature of the surrounding air, the temperature of the air used for heating different parts of the aircraft and so on.

The manometer is an instrument that measures the pressure of liquids or gases. Aircraft manometers are used to measure the pressure of the fuel entering the engine, the pressure of the compressed air, oxygen, hydraulic fluid and certain other liquids and gases.

According to the manometer reading the pilot controls the working of the engine's lubrication and fuel supply systems and determines the storage of oxygen and air in the aircraft tanks. Depending on the purpose of the manometers are named: "manometer," "fuel manometer," "air manometer" and so on.

The fuel gauge measures the quantity of fuel available in the tanks. From the readings of the fuel gauge pilot knows the quantity of fuel left at any stage in the flight. This enables him to determine the duration of the flight or to take in advance any decision regarding a forced landing due to lack of fuel.

The flow-meter is an instrument for measuring the flow of fluid per unit of time. With the help of flow-meter readings the aircraft crew can determine the quantity of fuel spent by the engine per kilometer of the distance traveled.

PICK-UPS AND SIGNALING DEVICES

Pick-ups and signaling devices are designed to alert the crew to any malfunction or to signal the operational condition of various aircraft systems and mechanisms.

The presence on modern aircraft of a large quantity of highly flammable fuel and its vapors creates a considerable danger of fire. So special pick-ups called fire detectors are installed in the engine section of the aircraft. They alert the pilot to any rise in temperature over the maximum permissible value. Usually a red light with a "fire" lights up simultaneously on the instrument. By pressing buttons the pilot puts into operation a system of fire-extinguishers which deliver compressed carbon dioxide from balloons and the threat of fire is eliminated.

While starting a jet engine it is necessary to know the magnitude of the minimum permissible fuel pressure in the low-pressure fuel line. For this purpose special manometers with electric warning lights are provided. The light goes on the moment the pressure in the low-pressure fuel system falls below the permissible minimum. A manometer with electric warning light is called a fuel pressure warning device.

There are also other pick-ups and signaling devices, for instance "generator off," "critical fuel storage," "afterburning," etc. In addition there are a number of signaling lamps installed on the instrument panel which indicate what condition this or that aircraft system or mechanism is in ("undercarriage lowered," "flaps normal" and others).

ELECTRICAL EQUIPMENT

Electrical equipment occupies an important place among modern aircraft equipment. This is principally due to the universality of electrical energy which is easily converted into other forms of energy: mechanical, thermal, light and chemical. Besides this it is possible by simply lowering or raising the voltage to distribute the energy between different devices comparatively easily: electric motors, lamps, heaters, radio units, etc.

Aircraft electrical equipment installations are simple to operate. They are light and compact and function reliably in flight.

The number of electricity-consuming devices on a modern aircraft is extremely large and grows larger every year.

On aircraft a 27 to 30 volt direct current electric supply is mainly used. On modern aircraft a three-phase alternating current supply with 200/115 volt and 400 Hz frequency has also found wide application.

The sources of electrical energy on board are direct current generators, alternators of special design with drive from the motor and chemical sources (storage batteries—lead or alkaline). When the generators are not working direct current is supplied from the storage batteries to the electric starters to start the engines and to the most important consumer devices (radio etc.) in an emergency.

To obtain high voltage direct current special transformers called converters are used. To obtain direct current in the alternating current systems rectifiers are used. To check the aircraft's aggregates with electric current after it has landed the electrical supply is taken from ground sources of electrical energy which are connected to the aircraft circuit through a special plug connector. This is done in all cases where no automatic device is installed, i.e. a generator with special motors.

All aircraft generators are provided with automatic regulators and overload protection devices. The regulators do not allow any deviation of voltage and frequency from the desired magnitudes, ensure the normal operation of electrical consumer devices and control the working of the generators.

Electrical energy obtained from the supply sources has to be distributed amongst a large number of consumer devices installed on the aircraft. For this purpose the electric circuit of every consumer device on board is provided with the quantity of energy required by it, as also the safety devices

which protect certain sensitive groups (mainly radio devices) from the disturbances of other devices consuming electrical energy.

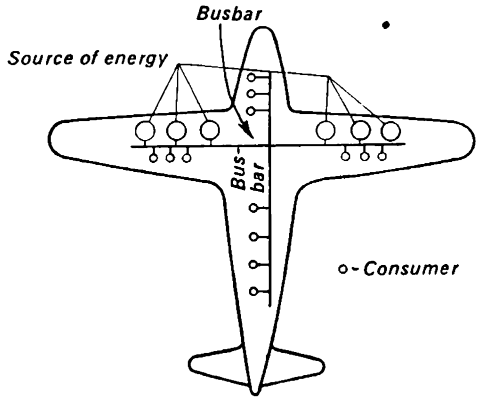


Fig. 58. Electric circuit aboard aircraft.

The electric circuit aboard an aircraft (Fig. 58) consists of wires, cables and busbars. Those wires which have metallic braid shielding for protection against interference from high frequency fields are called shielded wires. There are safety fuses for protection against overloads or short circuits, bimetallic or electro-magnetic safety automats, controlling devices (buttons, contactors, switches), circuit plug connectors, switching-distribution panels and other devices. In the case of direct current supply the electric circuit is usually single-wired, the aircraft body serving as the return wire.

The structure of the circuit aboard an aircraft consists of the main circuit which connects the generators, the distributor circuit which supplies energy to every consumer device through special connectors and the emergency circuit which is switched on automatically when the main circuit supplying the most important consumer devices goes out of order. On the majority of aircraft there is one central supply system in which all power sources operate in parallel in one system of busbars from which all consumer devices take their power.

In the event of failure of supply when one of the generators has gone out of order the consumer devices are automatically connected to the other generator.

The total length of electric circuits aboard aircraft is continually increasing. Not long ago the length of the circuit wires on large aircraft reached 40 km. On modern aircraft it now reaches 100–150 km.

On modern aircraft radio engineering, radio navigation and radar detection devices form an essential group of consumers of electrical energy.

A considerable part of the electrical energy is also consumed by electrical drives, i.e. electric motors and electrical mechanisms driving different parts of the aircraft and engine. They retract and lower the undercarriage, deviate flaps, operate control rudders and trimmers, close and open manholes, jet nozzle flaps, etc.

Much electrical energy is utilized by devices for starting the engines, i.e. by starters, fuel and oil pumps, etc. To start the engines, starter-generators

are used, which work as electric motors to turn the engine shaft. After that they are driven by the engine and work as generators.

Nowadays an electrical heating system designed to heat equipment and air entering the cabins is being generally adopted.

To maintain a given temperature automatically special automatic regulators are used. The regulator features a bi-metallic strip that closes the contacts whenever the temperature falls and opens them when it rises.

Similar thermo-regulators are also used in anti-icing systems.

During flights in cloud and fog subcooled drops suspended in the air in an unstable conditions impinge on the aircraft. A large proportion of them instantly freeze on surfaces of the aircraft, on leading edges of wing and tailplane, cockpit windows, air intakes, external antennas and so on. This phenomenon is called aircraft icing.

Icing is a great danger to an aircraft due to the considerable increase in flight weight with simultaneous deterioration of aerodynamic qualities and consequent decrease in lift.

On modern aircraft, therefore, thermo-electric de-icing devices are installed to keep the aircraft components free from ice. These devices consist of conducting strips laid over the surfaces to be protected through which an electric current is passed. On heating these electro-conducting layers the ice breaks up and crumbles and its particles are carried away by the free airstream.

Modern aircraft are equipped with high-quality and reliable lighting installations for operation in different conditions. They help the crew to prepare the aircraft for flight at night, carry out take-off, flight and landing in darkness, and provide comfortable illumination in the passenger cabins. To carry out all these tasks interior lights, exterior signals and landing lights are installed.

An aircraft's interior illumination provides the best conditions of lighting in the cabins and cockpit. For this purpose light sources are installed in all cabins and compartments of the aircraft, at the work places of the crew and at the tables for passengers.

The lamps used in aircraft are of small size, possess high illuminating power and have special holders to avoid self-loosening. Besides the usual incandescent lamps daylight lamps are used to illuminate cabins and corridors.

The local illumination of instruments and controlling members has great importante. Here it is important to provide good visibility of the instrument panel without at the same time lowering the night vision of the pilot's eyes and without revealing the cabin in the night sky. For this purpose the dials of instruments, levers, control sticks and switch buttons carry self-illuminating compounds. The luminescence of such compounds is amplified by the action of ultraviolet rays from special lamps.

Besides this special illuminating devices of various types are used for equipment. To these belong the lamps with flexible supports to which any shape can be given. Hinged lamps whose bulb can be turned and the light cast in the required direction also find application. Self-retracting lamps are of interest. When needed it is possible to move the lamp out of its cell and lower it. Thanks to a special spring the lamp returns to its niche when not required.

Exterior signal lights (Fig. 59) are used at night against possible collision of the aircraft in flight and on the ground and for signaling. Here, first of all, are the aero-navigation lights (BANO) that are installed on the outer surface of the aircraft. Two colored lights are located at the ends of the wings (port red, starboard green) and one light of white color in the tail of aircraft. The aero-navigation lamps usually burn continuously. Recently they have been made to flash.

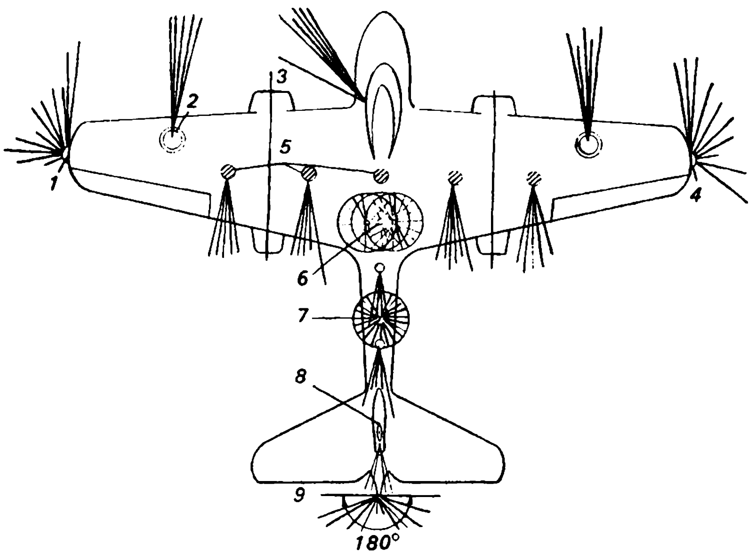


Fig. 59. Exterior light signaling system:

1—BANO red; 2—landing light; 3—manual luminous-signal lamps; 4—BANO green; 5—drill lights; 6—lower code lights; 7—upper code lights; 8—bomb marker; 9—BANO white

According to international standards aero-navigation lights are arranged in a definite form in order to enable an observer to determine the direction of flight of the aircraft. If the observer sees simultaneously both red and green lights this means that the aircraft is flying toward him. If one red or one green light is visible the aircraft is flying from right to left or

from left to right respectively. If one white light is seen the aircraft is flying away. Seeing all three lights means that the aircraft is flying either above or below the observer.

Besides aero-navigation lights there are drill lights of blue color on the aircraft. They assist the pilots in station keeping between aircraft in formation flying at night. These lights are mounted on the upper part or side of the fuselage. To signal from one aircraft to another and to the ground special code lights of various colors (red, green, yellow, white) are used. They are located on the upper or lower part of the fuselage. All of them can be switched on together or separately. They also can be used with a signaling key. During the Great Patriotic War these lights made it possible to identify our own aircraft during flight over an air base at night.

The landing illumination, which at nighttime or in bad visibility illuminates the runway and assists in landing, is of particular importance. It consists of aircraft landing lights and a steering light located on the leg of the front wheel. A landing light is a projector, small in size, but with an adequate light source with a luminous intensity as high as half a million candle power.

The total number of consumers of electrical energy on modern aircraft reaches 7,000 and their total power 600,000 watts. From foreign literature it is known that the prospects of further development of electrical equipment of aircraft and helicopters are great. Increasing flight speeds, altitude and range demand large-scale automation in controlling the power plant, flight regime and profile. With the object of providing more safety in carrying out flight tasks, which get more complicated year by year, flight navigation equipment will be more and more perfected, there will be new special automats and universal computers.

In its turn this will bring about a further increase in the power of the sources of electrical energy aboard and there will appear altogether new power sources. For instance, a plant using atomic energy or radioactive isotopes would provide a durable electric power source on board, according to foreign literature.

SECTION FIVE

Instruments and Method of Air Navigation

The first aircraft flew at low speeds and altitudes mainly in "flying" weather in daylight when it was possible to orient oneself easily. The years passed. Aircraft engineering was perfected, flight speeds and altitudes increased. The earlier methods of piloting based on "feeling the machine," rich experience and sometimes simply instinct could no longer satisfy the pilot. The pilot needed instruments that could help him to see the invisible horizon, execute the required maneuver, find the shortest path to the airstrip.

A magnetic compass become the first navigation instrument. Pilots in flight also resorted to orientation by the stars and planets, the sun and moon with the help of special astronavigation instruments.

Flight instruments soon appeared using the remarkable property of the gyroscope rotor (a fast rotating body) which maintains its position unchanged in space. Such instruments were called gyroscopic instruments.

Later on a complete group of instruments was installed on the aircraft using for a sensing element an aneroid box. These barometric instruments began to measure flight altitude and the speed of the aircraft, rate of climb and descent.

In the twenties of this century began the installation of radio instruments on aircraft. Today the cost of the radio instruments of a modern aircraft and the power plant, as a rule, considerably exceeds that of a glider.

Aboard the aircraft tens and hundreds of instruments are working to ensure the safety of air navigation, making it possible to fly at enormous speeds, at high and low altitudes, in any weather, by day and night.

MAGNETIC AND ASTRONAVIGATION INSTRUMENTS

The construction and working principle of a common compass are known to everybody. The compass fixed on an aircraft does not differ from it in principle. But the peculiarities of flight are reflected in this instrument.

A magnetic floating scale is placed in a brass box filled with spirit. The gradations on the transparent cover of the box show the division of the scale by which the aircraft heading is determined. So as to have a more accurate reading in the compass a deviating device is used which makes it possible to partly compensate the disturbing influence of magnetic fields aboard the aircraft formed around the wires carrying current and magnetic materials (iron, steel). It is possible to obtain the magnetic heading even more accurately by making the necessary correction determined by a special chart of deviation. The magnitude of correction depends on the aircraft heading.

Aircraft compasses are of several varieties. Compasses with a scale reading on the horizontal plane are more accurate. Those where the bearing is read on a vertical dial are more convenient. A remote reading compass makes it possible to simultaneously transmit the magnetic heading of the aircraft to all work places of the crew.

A compass made in our country (Fig. 60) is graduated in 5° divisions and works in a wide range of temperatures from −60 to +50°C with aircraft banking of up to 17°. It weighs not more than 150 g.

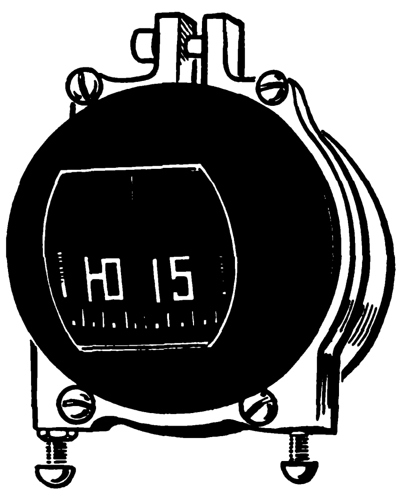


Fig. 60. Magnetic compass KI–13.

But magnetic compasses do have drawbacks. In polar latitudes their readings are unreliable. Sometimes instead of north the pointer shows south. Besides, a magnetic pointer cannot be used as a turn indicator due to its sluggishness.

During long-duration flights the navigator always tries to use astronomical methods for orientation of the aircraft. Astronavigation is especially important during flights in the arctic regions where use of a magnetic compass and radio navigation aids often becomes extremely unreliable.

To astronomical aids belong, first of all, the star globe. On it constella-

tions and stars are plotted. This globe enables the navigator to obtain a view of the starry sky as it appears at the place and time of observation.

In aircraft astronavigation usually the sun, the moon and the nearest thirty stars are used. In the northern hemisphere they include Alios, Polaris, Arcturus, Spica, Antares, Regulus, Aldebaran and Sirius. Taking into account the direction of the flight, the navigator selects the stars convenient for fixing the aircraft from the star globe. He finds their coordinates and, if necessary, determines their rising and setting times.

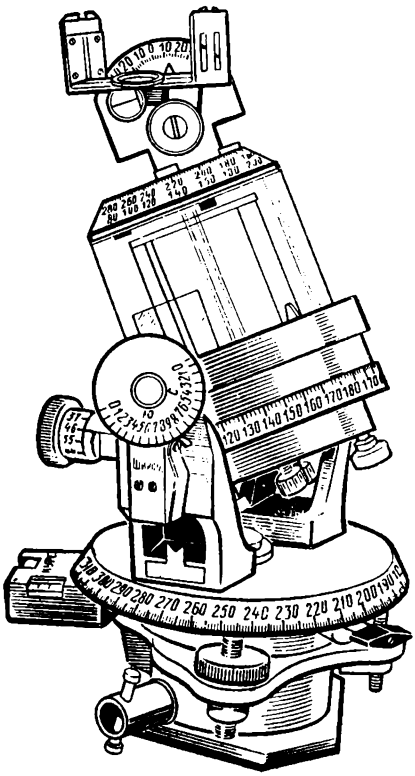


Fig. 61. Astrocompass with sighting device.

In order to determine the aircraft's heading it is necessary to measure the meridian of a star. For this purpose an astronomical compass (Fig. 61) with sighting device can be used. This sighting device has the shape of a clamp with a slit and front sight. The position of the sight in the horizontal and vertical planes is determined by the graticule. It is possible with its help to find the angle between the longitudinal axis of the aircraft and the meridian of the star. The magnitude of the measured angle is used to calculate the heading of the aircraft.

There exist astrocompasses (for instance, DAK–DB–5) which automatically show the true heading of the aircraft. In such compasses there is a photoelectric cell with a followup system which makes it possible to turn the photo-cell toward the sun. This continuously and automatically holds this direction irrespective of the position of the aircraft.

To determine the location of an aircraft during flight an air navigation sextant (automatic angle-measuring instrument) is also used. With the sextant, a so-called celestial altitude, i.e. the angle between the equatorial plane of the earth and meridian of a star, is measured. Knowing two celestial altitudes and the time of the first and second measurements, the navigator can plot on the graph the location of the aircraft after making

comparatively simple calculations with the help of special astronomical tables.

Optical astronavigational instruments are very convenient and simple in operation and have high accuracy. But their application is possible only when stars are visible. If the aircraft is flying through cloud the use of optical astronavigational instruments is impossible.

FLIGHTS BEYOND GROUND VISIBILITY

Pilots began to learn to fly beyond ground visibility more than 30 years ago. It was then common to see a scene like the following at an airport: A pilot boards an aircraft, with its cockpit windows carefully curtained by a tarpaulin cover. The cover was sealed in order not to tempt the pilot during flight. After receiving orders the pilot was supposed to take off, carry out a flight along a definite route and land at a given airport without once seeing the ground.

To fly under covers was essential because it was necessary to learn to fly in cloud, thick fog or a dark moonless night. And the pilot did not fly the aircraft blindly. He was accurately oriented by a number of assistants: magnetic, astronomical, gyroscopic and other instruments. They alerted the pilot to any change in flight direction, to turning speed and correctness of banking. Gyroscopic instruments made it possible to bring the skyline into the cockpit, i.e. the artificial horizon.

The instruments for flight beyond ground visibility work so accurately and reliably that the pilot uses them even in the daytime, in good weather when it is easily possible to see ground reference points.

GROUND RADIONAVIGATION INSTRUMENTS

Radio direction finder

An instrument with whose help the direction of a source of radio waves is determined is called a radio direction finder. If such a source of radio waves (transmitter) is installed on an aircraft then a ground radio direction finder[1] can determine the position of the aircraft.

To determine the aircraft's position the crew radios an inquiry to the head radio direction finder. After a certain interval the direction finder conveys the aircraft's coordinates or indicates the direction in which it must fly.

To determine an aircraft's coordinates it is necessary to have at least two radio direction finders placed at a sufficient distance from one another.

[1]There is lot in common in the working principles of ground and aircraft radio direction finders. Therefore the points considered here are to be kept in mind while reading the material that follows.

The position of the aircraft is determined by the point of intersection of the two lines (bearings).

The bearings (direction of the working radio stations on the map) in the simplest case can be obtained with the help of a common radio receiver provided with a special antenna. The antenna system used in radiogoniometry, as a rule, consist of two or more separate antennas receiving identical signals from all directions. The properties of such a system are expressed by the fact that depending on the direction of the radio waves received the total voltage obtainable from the antennas varies.

The dependence of the total voltage on the direction of the radio waves being received is called the radiation pattern.

In order to explain the working principle of a radio direction finder let us consider the radiation pattern of the most simple coil antenna.

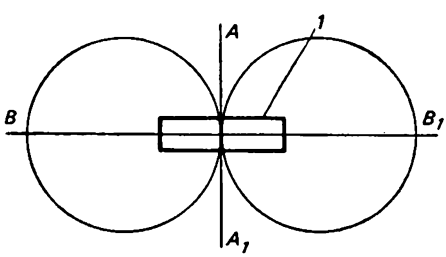


Fig. 62. Radiation pattern of a coil antenna.

Coil antenna: The radiation pattern of an antenna in the form of coil *1* with the vertical axis of rotation (Fig. 62) has the shape of a number "8" in the horizontal plane. This means that there exists a direction AA_1 from which there is practically no reception of radio signals. On the other hand, it is characteristic of the direction BB_1 that at the input of the receiver of the radio direction finder the signal is the most powerful one.

This radiation pattern of a coil antenna allows it to be used as a sensing element determining the direction of the radio waves being received.

The operator of a radio direction finder works in the following sequence: first he sets the frequency of the inquiring radio transmitter. Then by rotating the antenna he finds the position where the inquiry signal is not picked up. He then reads the direction of the radio transmitter from a special table and plots the bearings on the map.

The point of intersection of two bearings (the second bearing is conveyed by a neighboring radio direction finder operating simultaneously) determines the aircraft's coordinates.

In recent years semi-automatic and fully automatic radio direction finders which find the coordinates of an inquiring transmitter without any effort on the part of the operator have been used more frequently.

The radiogoniometry of an aircraft by ground radio direction finders does not demand the installation of any additional equipment (apart from a communications radio set), which by itself is extremely important. However, it has one disadvantage. In order to obtain its own coordinates the aircraft has first of all to ask for them and then after some time

receive the information. Considerable time is wasted.

Radio beacon

The position of an aircraft can be determined considerably faster than by ground radiogoniometry with the help of special radio transmitters termed ground radio beacons. There are many different types of radio beacons working on different wavelengths. Widely used, for instance, are radio beacons working on ultra-short waves (wavelength less than 10 m). For these waves it is possible to build an antenna with a narrow-lobed radiation pattern comparatively easily.

On turning the antenna the lobe of the radiation pattern slowly turns around the vertical axis and so to speak successively illuminates the whole of surrounding space.

The radio beacon continually transmits (for instance, every 5°) a signal giving the direction of radiation of electromagnetic energy. Having tuned the airborne receiver to the radio beacon (its position must be known in advance) the navigator hears the figures of bearings. The loudest figure itself is the bearing of the radio beacon with respect to the aircraft. To determine the position of the aircraft it is necessary to have one more bearing (and not necessarily from the second radio beacon). In spite of their low accuracy these "talking" radio beacons find application.

To increase the accuracy of the bearing (within 1°), in certain radio beacons instead of the signal being delivered by a voice some other signal, for example in the form of a slowly varying alternating voltage, is transmitted. According to the magnitude (and more often according to the phase) of the voltage the bearing on the aircraft is determined. Not surprisingly the construction of such a beacon and of the airborne receiving device is somewhat more complicated than that of a "talking" radio beacon.

Errors in determining the bearing of a radio beacon with high accuracy do not exceed some angular minutes. This is achieved by further complication of the construction of the radio beacon and airborne receiving device.

In the event of loss of orientation by an aircraft its coordinates can be determined by ground radar. The principle of radar operation will be explained below. Here we will only mention that there exist radars for various purposes: early-warning radars, taxi radars, precision approach radars and others. Special features of ground radar are high accuracy and long range.

AIRCRAFT RADIONAVIGATION INSTRUMENTS AND COMMUNICATIONS RADIO SETS

With increasing flight speeds and ranges radio navigation instruments began to be installed on aircraft for higher accuracy: first the radio direc-

tion finder, then radar, radio altimeter, instruments for landing beyond ground visibility and some others to provide accurate operation of ground radio navigation equipment.

Radio compass

An aircraft radio direction finder supplements the magnetic compass to a certain extent (and sometimes even fills in for it). It thus received the name of radio compass.

It is necessary to be more specific. Today the most automatic aircraft direction finding device, which automatically gives the heading on the radio station chosen, is the radio compass. There were also less automatic devices. They were called the radio semi-compass and radio maker.

The radio-semi-compass is an aircraft direction finder, originally with an antenna shaped like a coil. By manually rotating the frame of the radio-semi-compass the navigator (if the aircraft is a single-seater, the pilot) determines the bearing of the radio station chosen in advance. For this any radio station can be chosen provided it has an omnidirectional antenna and its frequency and position are known. The radio station located in the region of the airport where the landing is to take place is called the homing station.

By flying along a path such that the pointer of the course indicator stands in the center of the scale (at zero) the aircraft approaches the airport.

In order not to make an error of 180° while determining the bearing a common (non-directional) antenna is used. In the complex of the radio-semi-compass (Fig. 63), besides a bearing indicator (in multi-seater aircraft there are two of them) and two antennas there is a special radio receiver. Its construction and circuit have much in common with usual medium wave communication radio receiver.

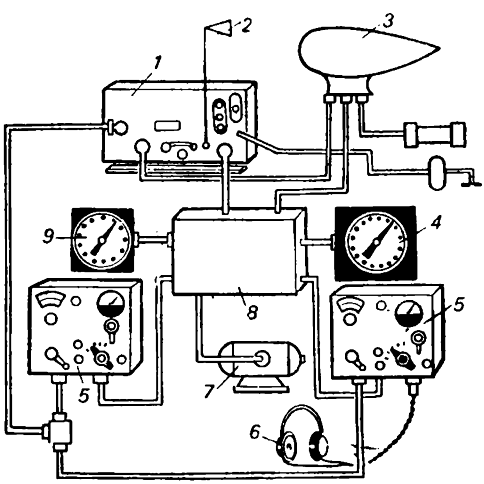


Fig. 63. Block diagram of a radio-semi-compass:
1—radio receiver; 2—nondirectional antenna; 3—coil antenna; 4—indicator for the navigator; 5—control panels; 6—earphones; 7—inverter; 8—distribution box; 9—indicator for the pilot.

The radio-semi-compass RPK-2 and RPK-10 were widely used in the Great Patriotic War. They were installed in almost all military and transport aircraft. Radio markers were a different version of the RPK-10.

These devices made it possible in addition to mark the moment of aircraft flight over the homing radio station.

The radio compass began to be widely used after the Great Patriotic War. In this instrument it is not necessary to manually set the coil antenna in the direction of zero reception. This is done automatically. The motor ceases to turn the coil at the moment when there is "zero" reception, i.e. when the plane of the coil is perpendicular to the bearing on the homing station. With the help of special electrical devices (synchro-transmitters and synchro-receivers) the position of the coil is fixed by a pointer indicator. If the reading scale is connected with the pointer of a magnetic compass by a suitable electrical device then the indicator of the radio compass gives the magnetic bearing of the homing radio station.

The indigenous radio compass ARK-11 makes it possible, besides solving purely radio navigational problems, to calculate the time and direction of aircraft landing by instrument landing systems which will be discussed below.

A radio compass is electrically remote-controlled and it is possible to tune to nine different pre-chosen frequencies in quick succession. It is evident that the receiver also ensures smooth tuning.

In the radio compass ARK-11 modern semi-conductors are widely used. During operation under conditions of large error there is a special regime designed for this radio compass for radio reception.

Radar

Radio location, using the property of radio waves of being reflected by the ground and objects (bridges, roads, cities, etc.) makes it possible to obtain a radar image and determine the distance (range) to these objects.

The phenomenon of reflection of radio waves (from sea vessels) was observed for the first time by the inventor of radio, A.S. Popov, in 1897.

The distance is measured as follows: A transmitting device radiates radio waves in short quantums called main pulses. Every main pulse with a velocity equal to that of light reaches the object whose distance is to be determined and is reflected from it.

A large number of experiments carried out by scientists showed that the velocity of propagation of radio waves in space depends very little on the ground conditions, conditions of the atmosphere, season or time of day and is a constant quantity, roughly equal to 300,000 km/sec. The reflected radio pulse or, as it is called, the "blip" returns with the same speed to the transmitter. If a receiver is installed near it then with its help it is possible to receive the blip.

In order to determine the distance it is sufficient to know the time lapse between the moment of transmitting the main pulse and that of receiving the blip.

In radar the time is measured by an electronic method in a special device. The distance is measured directly from the screen of a cathode ray tube similar to that of a common television set in its working principle and external appearance.

On this indicator signs in the form of light spots are illuminated. They correspond to the main pulse and blip. Using the scale plotted on the screen to the time scale the distance in kilometers to the object is determined by the distance between these signs.

The signs from different objects situated in the same direction but at different distances from the radar are located on the screen in one straight line but at different distances.

It is often sufficient to determine the distance to the object if the object is identified. But sometimes it is necessary to obtain the image of the ground or sea surface along with the objects situated on it, or in other words a radar map of the place is necessary.

Obtaining a radar image is based on an important property of radio waves, which are not reflected identically from different objects. The magnitude of the reflected signal varies in accordance with the size and properties of the reflecting surface.

Radio waves are well reflected by land, ships, iron bridges and structures and are least reflected from a water surface. The better the radio reflecting ability of the object the larger is the magnitude of the blip. A large blip illuminates a brighter spot on the indicator screen. Therefore objects reflecting the radio waves will create on the screen a spot brighter than the blip from a water surface.

Let us assume that it is necessary to search for a ship at sea. We will move the direction of the radiating main pulses in the horizontal plane (along with the azimuth). These pulses will then successively illuminate first the sea, then the ship and finally the sea again. The blips from the sea surface will show up as a weak light spot on the screen in comparison with the blips from the ship. Therefore on the screen there will appear a bright spot on a light background—the ship sought.

It is necessary to note that radar for detection of objects radiates not one but a number of main pulses in succession and obtains the same number of reflected ones. The fact is that the energy of the blips is very small and in order to obtain a clear image on the indicator screen it is necessary to deliver on it up to ten and sometimes many more signals for one object sought. The next main pulse is not radiated by the transmitter unit until the receiver receives the blip from the previous main pulse. Otherwise superimposition of signals takes place and the radar receiver cannot work.

Antenna. A radar antenna consists of a source of radio radiation (radiator) and a reflecting mirror (reflector). The radio beams from the radiator, after falling on the reflector, are reflected from it according to

the laws of optics and "illuminate," as it were, a narrow sector of the locality.

The geometrical dimensions and shape of the reflector for a given radiated wavelength determine the angular dimensions and shape of the sector where radar radiation is being directed. This zone can be obtained graphically.

Usually two graphs are given, one in a horizontal plane and the other in the vertical one. These graphs are called radiation patterns in the horizontal and vertical planes respectively.

Depending on the purpose of radars their antennas have various radiation patterns. For panoramic radar used on aircraft to obtain a radar map of the site the radiation pattern resembles a wide fan directed toward the ground. The width of this "fan" in the horizontal plane varies from fractions of a degree to several degrees. In the vertical plane it is wide and the width is in tens of degrees.

Designers always strive to obtain a narrow beam because the narrower the beam the finer the objects on the site that a radar can "see." Or, as the specialists say, a radar with a narrow beam has a good resolving power.

The antenna rotates at a speed of some tens of rotations per minute with the help of an electric drive. During its rotation the radio beam "sweeps" a considerable portion of the site. The radius of this portion, as shown in Fig. 64, can reach 150–250 km.

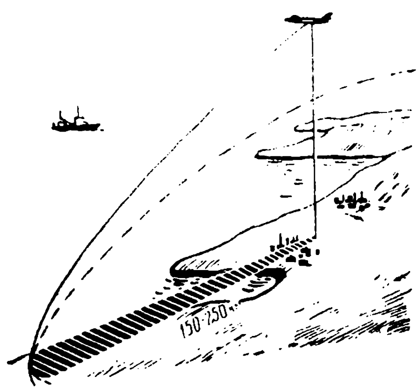


Fig. 64. Illumination of the ground surface by aircraft radar (hatched portion).

The impulse principle of operation of radar makes it possible to use one and the same antenna to transmit main pulses and receive the blips. This is very important since to install two antennas of 1–1.5 m size each on an aircraft would be an extremely difficult task.

The antenna hurts the aerodynamic properties of the aircraft and occupies much useful space. It must never be accommodated inside the aircraft since the metallic fuselage would absorb the radio waves. It therefore becomes necessary to accommodate the antenna on the exterior of the aircraft in a special housing (cowl) of material transparent to radio waves.

A cowl with the antenna is mounted in the aircraft's nose or under its fuselage. To reduce the drag it is made in the form of a hemisphere or half a pear.

Transmitting equipment. It is designed to generate high-frequency main pulses with the frequency corresponding to the operating wave of radar (aircraft radar usually operates in the centimeter wave band).

The power of high-frequency pulses or, as it is called, the impulsive power of the transmitter, must be very large. This is due to the fact that the electromagnetic radiation of radio pulses is absorbed and partially dissipated by the atmosphere. Besides this it is very important for the reliable operation of radar to obtain blips of sufficient strength, for which it is necessary to raise the strength of the main pulses.

The objects to be detected by radar are illuminated by pulses whose strength is measured by tens of kilowatts. But the strength of the blips received is very often considerably less than one billionth of a watt.

The transmitter generates a high frequency pulse of large strength only for a very short interval of time equal to 0.5–1.5 micro-secs. Depending on the range of radar the transmitter "gives out" some hundreds to some thousands of such pulses in 1 sec. In the intervals between the pulses the transmitter as it were "takes a rest," storing up energy from a relatively low-powered supply source.

The high-frequency pulses in transmitting equipment are produced by special electro-vacuum valves known as magnetrons. This takes place as follows: inside a copper vacuum chamber of the magnetron a cylindrical cathode is placed. The chamber, whose inner part usually has the shape of a ring with figured notches, itself acts as the anode. The magnetron is situated between the poles of a powerful magnet whose field also takes part in creating high-frequency oscillations inside the magnetron.

From a special device called a modulator high voltage pulses enter the magnetron. Within 0.5–1.5 micro-sec of the action of this voltage the magnetron produces (generates) high-frequency main pulses which then go to the antenna radiator through a waveguide.

The transmitting equipment is a separate block pressurized by air pump. Pressurization is essential because at high altitudes where the atmospheric pressure is small the insulation properties of the air are bad. Under such conditions high voltage electrical breakdown and failure of transmitting equipment are possible.

Receiving equipment. The electro-magnetic energy reflected from objects is received by an antenna and comes to the radar receiver through the waveguide, However, the signals received cannot be delivered directly to the indicator screen as they are very weak. It is necessary to amplify them and convert them into video pulses preserving only the shape of the signals received. Such pulses are free of the high-frequency oscillations which are received by the antenna of the transmitter.

The device that converts a high-frequency signal into a video signal is called a detector.

Since the strength of the blip is small the sensitivity (receptiveness) of the receiver must be quite high. For the sake of comparison we will note here that modern television sets have a sensitivity (receptiveness) some hundred times inferior.

Let us briefly study the peculiarities of radar receiving equipment. In such devices, as a rule, a circuit making possible a large amplification of the signals received is used. For this purpose the high-frequency signal received is mixed with the signal from an additional generator (oscillator). The mixing takes place both in the mixer diode and in the usual mixer of a broadcasting radio.

At the exit of the mixer a pulse voltage of intermediate frequency, usually 30 to 60 MHz, is delivered. A voltage of such frequency can be amplified comparatively easily. For the purpose of amplification there are six to eight cascades of intermediate frequency amplifiers. The amplified pulses enter the detector (crystal diode) wherefrom the high-frequency pulse its envelop is given out as a video signal.

Superoscillating radar receivers differ from broadcasting and television receivers by the fact that as an oscillator a special electro-vacuum device known as a klystron is used, while a crystal diode is used as a mixer.

From outside a klystron resembles a common radio valve. It is a generator of auxiliary high-frequency oscillations used for conversion (with the help of a mixer) of blips into pulse oscillations of intermediate frequency.

The klystron is used in radar not only due to its ability to generate high-frequency oscillations. Even an ordinary radio valve can produce such oscillations. The most important property of the klystron is to vary the frequency of the oscillations generated on varying the voltage at its anode (reflector electrode). This property of the klystron makes it possible to use an automatic frequency control system in the receiver and thus change the tuning of the receiver without the operator's intervention.

The necessity of receiver control arises due to insufficient operational stability of the radar transmitting equipment. The fact is that the magnetron of the transmitter, under the influence of a number of factors, arbitrarily varies its frequency and, consequently, the frequency of the blips.

If the receiver has fixed tuning while the frequency of the signals received varies, then no stability of reception of blips is possible. Therefore an automatic frequency control system is used in the receiver, making possible the automatic control of the frequency of the klystron in accordance with the variation of blip frequency.

Synchronizing and indicating devices. In order to determine the distance of objects a "clock" that can measure time with an accuracy up to some microseconds is needed in the radar. Such accurate measurements have become possible due to the use of crystal clocks.

A crystal plate placed in a variable electrical field is capable of creating in the oscillating circuit of a high-frequency generator oscillations of a particular frequency directly proportional to the geometric dimensions of the plate.

This property of crystal made it possible to build a generator with the help of which a very accurate measurement of time was achieved. The high-frequency oscillations of such a generator are converted into a sequence of electrical pulses, one following the other at equal intervals of time, for instance 13.333 microseconds. By this time the main pulse would travel 2 km and, having been reflected, return (1 micro-sec in radar corresponds to 150 m).

By delivering "commands" to the transmitter, modulator, receiver and indicator the crystal clock makes them operate synchronously and creates on the indicator screen scale marks by which the distance of the objects detected is determined.

The basic indicating device is a cathode-ray tube. The deflector of this tube makes the electron ray traverse its screen in the required direction.

While traversing it under the influence of the deflection yoke the ray forms something like a grid-sweep array. Sometimes the deflection yoke causes the ray to move on the screen along other paths, for instance from the center along the radius. The ray begins to move along the radius of the screen (radial sweep) with a signal from the crystal clock simultaneously with the radiation of the main pulse and, at the time of radiation of the next main pulse, completes its movement toward the tube rim (approximately after 500 to 2,000 microseconds depending on the set scale of radar range).

Simultaneously with the radial movement of the ray the deflection yoke turns the sweep about the tube axis in synchronization with the rotating antenna (nearly 20 rotations/min). Due to this dual motion of the ray a circular array occupying the whole area of the screen is obtained.

The blips enter a controlling electrode of the tube from the receiver and, depending on their magnitude, amplify the electronic beam, proportionally increasing the illumination of the screen and spotlighting the objects from which they were reflected.

The electric signals of time from the crystal clock are also constantly fed to the controlling electrode. These signals create on the screen bright concentric scale rings located at an equal distance from each other. The distances of the detected objects are determined from these rings.

The applications of radar

Besides the basic task of survey of the ground surface many other navigation tasks are also laid on aircraft radar.

Radar enables the crew to detect mountains and thunderclouds. By observing thunder fronts the pilot can choose zones (corridors) where thunder-

storm activity is weakest and does not obstruct the safe flight of an aircraft. Besides this radar can be used for operation with ground and aircraft transponder-beacons. On the indicators of the aircraft radar the ground transponder-beacons, whose location is known in advance, are illuminated by bright spots. The spots from the transponders flicker. According to the frequency of flickering the location of the transponder is determined and the thanks to this the location of the aircraft.

In cases where the danger of aircraft collision arises radar warns the pilot by switching on a special danger signal light.

The transponder-beacon consists of a receiver and a pulse transmitter. The transmitter starts working only when the receiver picks up a signal. The receiver and the transmitter are tuned to the operational frequency of the aircraft radar. The receiver outlet is connected to a device that controls the operation of the transmitter.

If an aircraft radar sends a main pulse and the receiver of a transponder-beacon receives it a controlling signal from the receiver outlet is fed to the transmitter and makes it radiate an answer signal (something like a blip).

The aircraft receiver receives the signal and delivers it to the radar indicator screen where it places a mark whose range and azimuth correspond to the distance and bearing between the transponder-beacon and the aircraft.

By comparison with the weak blip on the indicator screen received from local objects situated near the transponder-beacon the signal of the transponder-beacon transmitter is much more powerful. This considerably increases the radar range in working with transponder-beacons and eases the navigator's work.

Transponder-beacons built on the same principles are installed on aircraft to increase their reliability and range of detection of other aircraft equipped with radar.

Radio altimeter

It is essential for the crew to know the exact flight altitude of an aircraft while landing, solving navigational problems, for ensuring flight safety especially in difficult meteorological conditions and while flying over hilly areas.

On aircraft of old types only barometric altimeters were used. Such altimeters, however, cannot measure the true flight altitude over the ground. They show barometric flight altitude relative to the airport or sea-level taken as the datum level. The true flight altitude can be determined by measuring the time between the moment of transmitting a radio-signal and the moment it is received after being reflected from the ground.

A radio altimeter consists of a transmitter, receiver, transmitting and receiving antennas and altitude indicator. For measuring medium and large altitudes (10 to 15 km) radar is usually used.

The high-frequency energy pulses generated by the transmitter having a strength of some watts are radiated by an antenna in the direction of the ground. These signals first reach those points of the ground surface which lie directly under the aircraft.

The signal reflected from the ground reaches the receiving antenna and is fed to the receiver where, after transformation, it is delivered to the indicating device. In the indicating device the time interval between the times of radiating the main pulse and receiving the blip is calculated by an electronic method. The true flight altitude can be read on the cathode-ray-tube screen with circular scanning by the distance between two electron markings corresponding to the main pulse and the blip.

Radar altimeter cannot be used to measure low altitudes since its "altitude ability" is limited by the duration of the main pulse. If the duration of a main pulse is 0.2 micro-sec then the accuracy of measuring flight altitude is 30 m. During flights at low altitudes and especially during landing, therefore, it becomes necessary to use radio altimeters built on other (frequency) principles of operation.

The essence of the working of altimeters with a frequency method of measuring altitude lies in the following: The transmitter antenna of a radio altimeter radiates a continuous high-frequency signal in the direction of the ground. The frequency of the radiated signal varies slowly within small limits according to a program set in advance. When the blip reaches the receiving antenna its frequency differs from that of the signal that is being radiated at that moment by the transmitting device. The greater the time lapse (the larger the flight altitude) between the moments of rotating and receiving the signal, the larger the difference in frequencies. By measuring the difference obtained the true flight altitude can be determined.

In the receiver there is a special mixer of main (straight) signals and those reflected from the ground. As a result of interaction of these signals of different frequencies at the mixer exit there forms a voltage which is proportional to the difference in frequencies, i.e. to the flight altitude. This voltage is fed to a pointer altitude indicator having a scale graduated in meters. A pilot easily reads off the true flight altitude from this indicator.

The accuracy of this altimeter is very high. It can also show a change in terrain relief and the presence of prominent structures. Therefore this type of radio altimeter is indispensable in the absence of ground contact during flight and landing.

On the aircraft Tu–134 a low altitude altimeter RV–UM is mounted. The range of altitudes that can be measured is from 0 to 600 m with an accuracy of roughly 5 m. The power required is 120 watts.

This altimeter has an important feature. It has a signaling circuit that warns the pilot about deviation of the aircraft from the set flight altitude,

which is necessary especially during flights at low altitudes. With the help of a signaling circuit switch the pilot sets a preselected altitude below which the aircraft must not descend under any circumstances.

It is possible to set many such altitudes (every 50 m over the whole range of measurable altitudes). The signaling scheme works when the aircraft descends to the set altitude. On the instrument panel, a red lamp "danger altitude" burns (flickers) and an interrupted sound signal is given out. These signals warn the pilot: "Be careful, climb above the danger altitude."

Aircraft radio stations

To provide communication on an aircraft some radio stations operating on different wave bands are installed. These radio stations differ from ground stations in small weight and size. According to the purpose they are classified as command radio stations and communications radio stations. On large passenger and transport aircraft up to three complexes of stations are usually installed, two of which are command stations. The latter operate in a telephonic regime and are used for communications with the command radio stations of control posts and also between aircraft.

The first low-power (up to 10 watts) command radio station of type RSIU–5 operates in the meter band of waves only in the telephonic regime and is used for short-distance communications. Thanks to crystal stabilization of frequency the radio station provides communication on many channels set in advance. The operational range is up to 300 km.

The pilot controls the radio station at a distance from a special panel with many buttons which allow automatic tuning of transmitter and receiver to the required communication channel. Changing from one channel to another takes some seconds.

There is only one antenna for transmission and reception. It is automatically connected to the transmitter or receiver with the help of a special switch. The antenna can be made in the form of a flat brass sieve glued between two insulator plates located on the aircraft fin.

The second command radio station of type RSB operates in short and medium wave bands. This station is used for telephonic and telegraphic two-way long-distance communication of the aircraft with ground stations and with the airborne radio stations of other aircraft.

The range of operation is 2,500–3,000 km. The power required by the transmitter varies from 5 to 80 watts depending on the operational regime (telegraphic or telephonic) and the operational frequency selected.

It is a known fact that with short waves it is possible, even with a comparatively low-powered transmitter, to provide very long-distance communication due to the radio beam being reflected from the ionized layers of the atmosphere.

However, short wave communication is not always reliable because the ionized layers change their height and reflecting properties all the time. Besides, over this band a steep attenuation (fall of transmission loudness) due to the nonuniform generation of short radio waves is observed, especially in the polar regions. Usually medium wave bands, less sensitive to errors, are used.

To control the transmitter is quite easy. Before take-off the radio operator tunes the transmitter manually by using a crystal calibrator to a certain number of (about ten) communications frequencies selected in advance. Retuning of the transmitter during flight is carried out with the help of a special automatic device that turns the tuning knobs of the transmitter to the positions set by the radio operator. The control of automatic tuning is carried out from the radio station control panel by a common switch.

The retuning of the transmitter from one channel to another takes 20–30 sec. The transmitter is activated by the radio operator's microphone or the pilot's microphone (special throat microphones) or from a common telegraphic key.

A radio complex includes a superheterodyne-type receiver. It has shortwave, mediumwave, and longwave bands. The receiver can take on both telephonic and telegraphic work. I thas automatic and manual controls for sensitivity and a regulator to improve operation under erratic conditions.

There is only one antenna for both receiver and transmitter. It is in the form of a bi-metallic wire stretched between a fin and the fuselage of the aircraft. Sometimes a so-called loop antenna is used which is located in a plain cowl—a metallic tube fixed at a small distance from the fuselage along its length. It is automatically connected either to the transmitter output or to the receiver input by a special switch.

A communications radio providing constant long-distance communication with ground and other aircraft as a rule, operates in the telegraphic regime. Usually the second set of command radio stations described earlier is used as such a station.

INSTRUMENT LANDING SYSTEMS

The flight of aircraft at night and under conditions of bad visibility became possible only after the difficulties of instrument landing of aircraft ("blind" landing) were solved.

For the first time in the world a blind landing system "Noch'-1" was worked out in the Soviet Union in 1930. Soon afterward a new radio landing system was suggested by N.A. Korbanskii. Instrument landing systems became widely used in the 40s of this century. In the beginning

they were the blind landing systems. Although the equipment of blind landing systems is cheap and fairly simple their technical capabilities are not high. An air-borne radio compass, radio stations (the ground homing stations and aircraft communication stations) and optical means on the ground (projectors, lights) served as the basis of such a system.

A pilot or an aircraft navigator was supposed to compute the landing himself. Such computation not always being accurate, aircraft sometimes landed on the runway after many unsuccessful attempts.

OSP system with homing radio stations

Aircraft equipment providing landing with the help of a blind landing system includes a communication command radio, automatic radio compass, marker radio receiver and low-altitude radio altimeter.

The ground equipment includes a marker beacon (MRM) which is a low-power transmitter whose antenna radiates electro-magnetic energy only upward. These transmitters are installed along the landing path (direction) at definite places (Fig. 65).

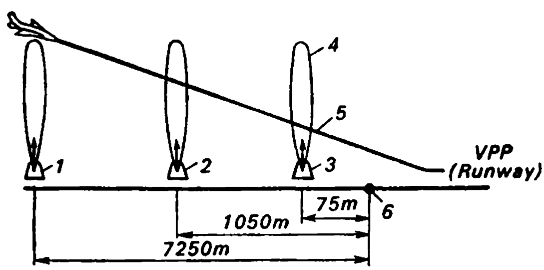


Fig. 65. A typical scheme of arrangement of marker beacons during landing of aircraft with the help of blind landing system:

1—outer MRM; 2—middle MRM; 3—boundary MRM; 4—radiation pattern; 5—aircraft landing path; 6—runway start.

The antenna of the aircraft marker radio receiver receives the MRM signals only at the moment when the aircraft is flying overhead. The receiver is always tuned to the frequency of MRM. At the time of overflight the receiver automatically reproduces (by light and sound signal) its signals.

According to the nature of the signal (intermittent or continuous) the crew determines the exact distance of the aircraft from the start of the runway.

With a blind landing system the landing of aircraft takes place in the following manner: after entering the airport zone with the help of a radio compass tuned to the other homing radio station the pilot asks permission to land and the landing conditions over the command radio. He then

executes an accurate approach maneuver. After having passed the outer homing radio station (the moment of overflight is determined by the signals of the marker radio receiver) the automatic radiocompass is switched over to the inner homing radio station.

The frequencies of homing radio stations are usually so chosen that this changeover is carried out by simply turning the band switch of the radio compass. While working with the radio compass ARK–11 it is sufficient to press the button corresponding to the particular frequency.

After having verified the landing path computation the pilot continues to descend. After passing the inner homing radio station (at this moment the signal of the marker receiver from the second MRM goes into action) the pilot now executes the landing visually with illumination aids. About the beginning of the runway the third MRM signals the pilot. Incidentally, during landing the pilot also uses the flight-navigation instruments described earlier.

Instrument landing system with localizer and glide-path beacons

In comparison with the blind landing system the system using a localizer and glide-path beacons is more perfect. It makes it possible, firstly, to reduce the time required for landing which increases the traffic carrying capacity of airport; secondly, to execute a landing in more difficult meteorological conditions; thirdly, to organize the despatcher service of the airport comparatively easily since the instruments of the system simultaneously detect and identify aircraft and also determine their distance. The last task is carried out with the help of surveillance and control room radar and automatic range finders.

This system, besides the runway heading and the distance to the point of landing, also gives the line of descent, i.e. the glide-path. By flying according to the heading and glide-path the pilot descends to 50 to 60 m above the ground. Landing from such a height is possible as a rule with lighting aids.

The ground equipment of the system includes a localizer and glide-path beacons, an azimuth-range finder beacon, retransmitter of the range finder, marker beacons and similar equipment.

Besides the landing approach (according to heading and glide-path) this system makes it possible also to plan a visual touchdown and to carry out some other tasks: constantly to fix the aircraft location with respect to ground beacons; to fly the aircraft on any straight route passing over the ground beacons or not passing over them; to fly the aircraft along a curve; and to penetrate the clouds along the trajectories permissible for a given type of aircraft. On the ground observation indicator it is also possible to observe the identification markings of aircraft.

The ground localizer and the glide-path beacons operate on the principle of the equisignal zone. The equisignal zones of KRM and GRM are directed along the runway axis in such a way that they enable the pilot to execute a correct landing approach without airport contact.

A ground automatic range finder is a pulse retransmitter. With its help the pilot determines the distance to the airport. A special aircraft transmitter radiates inquiry pulses in the frequency of the ground range finder. These pulses are received by the receiving equipment of the range finder, amplified and reradiated by the range finder transmitter. The reply pulses return to the aircraft's receiving equipment only after a certain interval of time. On the basis of the interval of time the distance to the airport is estimated.

The aircraft equipment of the instrument landing system is fairly complicated. In addition to the receiver and transmitter of the automatic range finder and the equipment necessary for the blind landing system, localizer and glide-path radio receivers are used. The latter have a common indicator which is used by the pilot while descending along the glide-path. If the aircraft descends correctly the pointers of the indicator remain crossed in the center of the instrument. If the aircraft deviates from the course or flies above (below) the glide-path the pointers of the instrument immediately indicate the error.

GROUND-CONTROLLED LANDING SYSTEM

Installation of special equipment on the aircraft is not required for the operation of such a system. It is quite enough for the command or communications radio to operate reliably. The aircraft's coordinates are determined on the ground and only commands regarding change of course, altitude and descent regime are delivered to the pilot. Indeed, any aircraft having radio communication with the airport can land using this landing system.

To determine the coordinates of an aircraft making a landing approach ground radar with high accuracy is used. Usually there are two of them. One helps to bring the aircraft into the zone from where the landing approach begins, the other takes over in the landing zone.

There have already been fully automatic landing systems in operation. Commands for landing are fed to the airborne computer whose output is connected to the autopilot and the aircraft speed regulator. Data regarding the aircraft's altitude are also fed to the computer. It is assumed that the aircraft will land on the runway and taxi to its parking place automatically only under the observation of the crew.

SECTION SIX

Aircraft Cybernetics

THE PILOT CONTROLS THE AIRCRAFT

The pilot is the central figure of a modern aircraft. The basic task of cybernetic devices is, therefore, to reduce the work of the pilot to a minimum and to help solve any problem confronting him.

Let us consider the function of a pilot in a scheme of aircraft control (Fig. 66). In the cockpit right in front of the pilot there is a panel of the most diverse control instruments. After consulting them the pilot adjusts the air controls (or engine control rod) suitably in order to maintain the flight strictly in the given regime.

Let us assume that the pilot is supposed to carry out the flight at a set altitude. The air ocean is never calm. By getting into a jet stream, for instance, the aircraft can suddenly lose some tens of meters. This is immediately shown by the altimeter. On the instrument panel there would be, as they say in cybernetics, the so-called "commentator" giving this information to the pilot: "Flight altitude less than the one set."

In accordance with this information, or so to speak, reacting to it, the pilot pulls the control stick toward himself. The controlling signal (the controlling information) is thus sent to the system operating the aerodynamic controls. Through the hydraulic actuator the elevator is deviated upward and the aircraft begins to gain height until it reaches the desired altitude. The pilot knows about it when the needle of the altimeter returns to the set division, i.e. the "commentator" gives the information on the instrument panel: "Flight altitude equal to the one set." Thus the cybernetic control loop is closed.

The upper part of the loop from aircraft to instrument is called feedback (Fig. 66). Thanks to feedback it is possible for the pilot to check to

what accuracy his command has been executed. The presence of feedback is the typical feature of all cybernetic systems and devices.

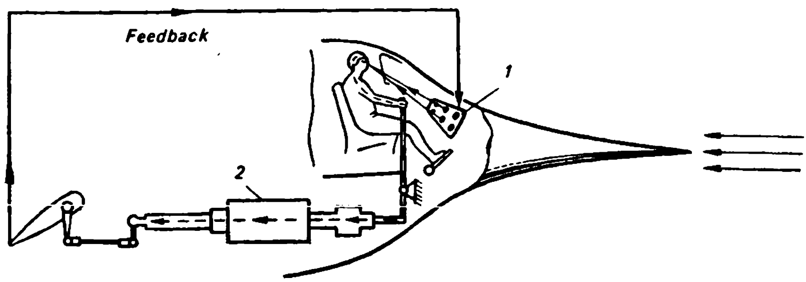


Fig. 66. Scheme of aircraft control:
1—instrument panel; 2—hydraulic actuator.

FLIGHT SIMULATION

Very often the instrument readings alone are quite insufficient for a pilot to carry out his assignment successfully. The pilot must work out the information obtained from the instruments, decode it and only then use it to fly the machine. The pilot has to carry out many mathematical operations while planning landing maneuvers and during long-range flights. And here to help the crew comes "little cybernetics," the computing instruments and devices.

Until recently on aircraft the so-called analog computers or, as they are also called, continuous operation computers were used as computing instruments.

They free the pilot from tiresome and monotonous mathematical operations. For this purpose a so-called electronic "flight simulator" is used. Every physical quantity figuring in the navigational problem to be solved (for instance, acceleration, speed, course) is represented in the simulator by some other corresponding quantity, for instance, electrical voltage, angular velocity of the engine shaft and so on. The extents of variations and the scales of quantities are chosen from the conditions of the assignment.

All that takes place during the operation of the simulator is the mathematical analogy of the actual physical assignment. Therefore the simulating computing devices are often called analog machines.

Every physical quantity (basic air speed, banking angle and so on) can assume any value within certain limits. Consequently the corresponding quantities in the simulator which are the signals of navigation parameters also vary continuously. The process of solving the problem of determining coordinates, course lay-out, etc. is also carried out continu-

ously. As a result the analog-machines earned the name continuous operation computers. As continuous operation computers, integrators, adders, trigonometric and multiplying devices are used.

The integrator converts the incoming signals into a signal of some other form that is mathematically described by an integral (usually with respect to time).

The computer that measured the speed of some experimental German rocket, the *Fau-2*, can serve as an example of an integrator.

An electric cell *RC*, i.e. a combination of resistor and a condenser, can be used as an integrator. The fact is that the condenser voltage is proportional to the integral of the charging current. The voltage of the condenser is the output voltage of the integrator while the magnitude of the charging current must be proportional to the incoming signal.

The adder is a device that sums up algebraically the information from two or more sources of information. For the adder to operate accurately it must add the signals in correct proportion with the corresponding sign and amplitude.

The type of adder to be used depends mainly on the type of aircraft cybernetic system. The majority of cybernetic systems are made up of electronic instruments, so the majority of adders are electronic. In principle they can be pneumatic, hydraulic or mechanical.

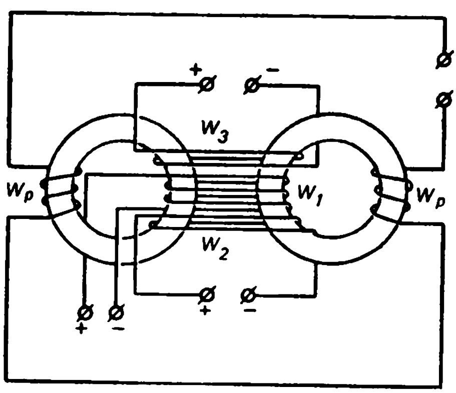


Fig. 67. Adding with the help of magnetic amplifier:

W_1, W_2, W_3—control windings; W_p—operating winding (the current in the operating winding is proportional to the sum of voltages fed to the control windings).

Adders consist either of electric circuits that include potentiometers, inductive resistors and capacitors or of certain cascades of electronic valves. The most widely used are the summation circuits with the help of potentiometers, voltage dividers, control winding of magnetic amplifiers (Fig. 67) and bridges.

Trigonometrical devices to solve the problem of determining to position of the aircraft in flight the multiplication of a measured quantity, for instance speed (usually in the form of voltage), by the trigonometric function of a certain angle, for instance the course angle, is often used. To obtain the trigonometric functions of sine and cosine either sine-cosine potentiometers or rotating transformers are used. The more complicated trigonometric functions are obtained with the help of func-

tion potentiometers.

A function potentiometer is a flat insulated plate one end of which is cut along a curve corresponding to the required function. A conductor with high specific resistance is wound on the plate.

In Fig. 68 a secant potentiometer is shown. It consists of a constant resistance and a function potentiometer inserted just after it. The supply voltage is fed to the points A and B while the output voltage is taken at point A and slide-key D. If the resistance of the function potentiometer varies in proportion with the φ sec (φ—the latitude of flight vehicle location), i.e. if $f(\varphi) = \sec \varphi$, then the output voltage $U_{\text{out}} = U_{\text{in}} \sec \varphi$.

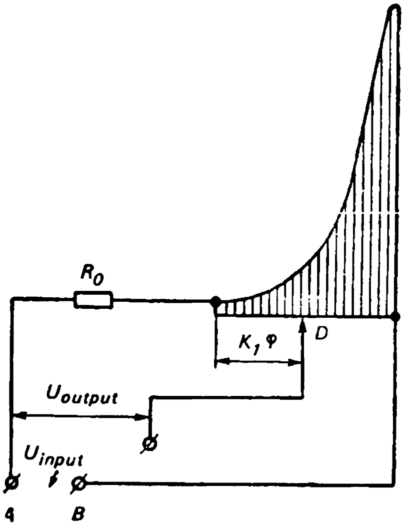


Fig. 68. Secant potentiometer.

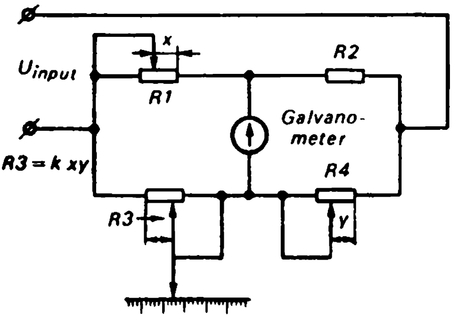


Fig. 69. Multiplier.

The electrical *multiplying devices* (Fig. 69) are meant for multiplication and division of two or more quantities. They can be made on the potentiometers by using bridge circuits and a logometer.

It should be noted here that the bridge circuits make it possible to carry out multiplication and division of quantities with considerably more accuracy than potentiometers do since the result of measurement does not depend on the resistance of load.

CYBERNETIC AUTONAVIGATOR

Without computers simulating flight the operation of modern navigation systems would have been unthinkable. The accurate determination of aircraft location at modern flight speeds and altitudes is impossible without using computer technology. The answer to the question how much of the course has been covered, how many kilometers remain to the destina-

tion, must not only be accurate but also instantaneous. Complicated navigational calculations often take too much of the crew's time. So on many aircraft now the navigational cybernetic devices termed autonavigators are installed.

Aerodynamic computer of course

A navigation system that automatically determines, on the basis of data supplied by the hydromagnetic compass and air speed indicator, the location of the aircraft at a given movement of time is called an aerodynamic course computer (Fig. 70). It includes a pressure head pilot tube *1*, true air speed pick-up *2*, course automat, two integrators *3*, *5*, and indicator of the course steered (coordinates counter) *4*.

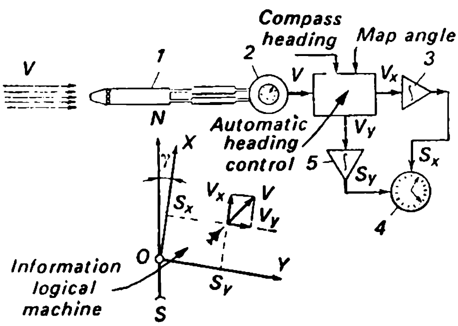


Fig. 70. Principle scheme of aerodynamic computer of course.

The principle of operation of an autonavigator is as follows: In flight the signals of the true air speed indicator are converted into an electrical form. For this purpose the true air speed pick-up is used. The higher the flight speed the larger the electrical voltage at the outlet of the pick-up. This voltage is fed to the course automat where, with the help of a multiplying device, it is multiplied by the sine and cosine of the course angle. Thus the vector is as it were resolved into two mutually perpendicular components: V_y—the component of the aircraft's true air speed along the direction of course and V_x—the component of true air speed perpendicular to the direction of the course.

As is known, the course covered is the integral of the speed. Therefore by integrating the component V_y the course S_y is obtained, i.e. the distance the aircraft has flown from the point O along the course. Analogically, by integrating the component V_x the course S_x is obtained, i.e. the distance by which the aircraft has been deflected off course.

The angle of the map is necessary to make the orientation of the axes of coordinates more convenient. In our example, the course line Oy does not coincide with the East-West line, i.e. it is not perpendicular to the North-South line. This complicates the calculations if the computation is carried out in the geometrical system of coordinates. By turning the geometrical axes about the point O through the map angle the new so-called conditional coordinate axes x and y are obtained. The course computation relative to these axes is very simple. The use of the autonavigator in flight

is also simplified: the pilot must fly the machine in such a way that the pointer of the indicator with index "x" stands all the time at zero. Then the pointer with index "y", like the speedometer of an automobile, will show the number of kilometers covered.

Inertial system of navigation

Although the autonavigator described above is self-contained, i.e. its operation does not depend on communication with the ground, it still has a number of inadequacies. Due to the insufficient accuracy of the true air speed pick-up, which besides measures the flight speed relative to the air and not to the ground, there are errors in determining the aircraft's location. Besides this, such autonavigators, as was shown by tests carried out on the experimental aircraft *North-American* X–15, become inoperative during flight in the upper layers of the atmosphere because the air is too rarefied there. Therefore the aerodynamic course computer has begun to give way to new cybernetic devices such as the enertial system of navigation.

The inertial system makes it possible to compute the flight speed and the course covered from the point of take-off on the basis of acceleration measured on the aircraft. This system does not need any external source of navigational information (in the air envelope around the earth) and radiates no energy whatever. It is therefore absolutely self-contained.

An aircraft guided with the help of inertial system is not vulnerable to jamming and other disturbances and an enemy cannot detect it in advance.

The inertial system of navigation usually includes such instruments as the accelerometer[1], gyroscopes, computing instruments and tracking electrical drives[2]. However, their use in the inertial systems of navigation became possible only in recent years when engineering achieved production and control of instruments of high accuracy that maintained the set parameters in a wide range of temperatures of the surrounding medium and through vibrations and shocks during the rapid accelerations at the moment of starting and on landing. All equipment in the inertial system of navigation is mounted in the aircraft.

The inertial system of navigation works as follows: It is known from mechanics that the force acting on a body accelerates it. The higher the force, the greater the acceleration of the body.

Acceleration of a moving body can be measured by a special meter of acceleration which is also the pick-up of the inertial system that catches the primary navigation information.

The simplest meter of acceleration (accelerometer) is the load with mass m suspended on springs (Fig. 71). It is possible to try carry out this experi-

[1]The accelerometer is an instrument that measures the acceleration of the aircraft.

[2]A tracking electrical drive is an electro-mechanical system consisting of an electric motor, reduction gear and a pick-up of the angular position of the shaft.

ment by mounting an accelerometer on a trolley and attaching to the load the slider A of a potentiometer fixed to the trolley base. If the trolley is stationary or moving uniformly the slider A touches the potentiometer at the point B and between the points A and B there is no potential difference.

Under the action of an applied force F the troelly receives acceleration a. The load m is displaced relative to the platform base until the force F is balanced by the tensile and compressive forces of the springs. The quantity of displacement Δx is proportional to force F and, consequently, to acceleration a. Between the slider A and point B there appears a potential difference by a quantity which is proportional to the acceleration. The sign depends on the direction of acceleration. If the trolley were stationary then, from the magni-

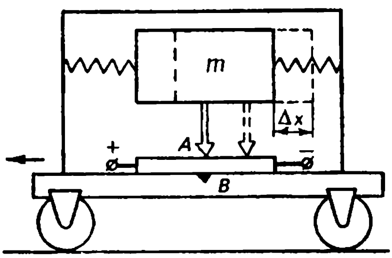


Fig. 71. A trolley with an accelerometer.

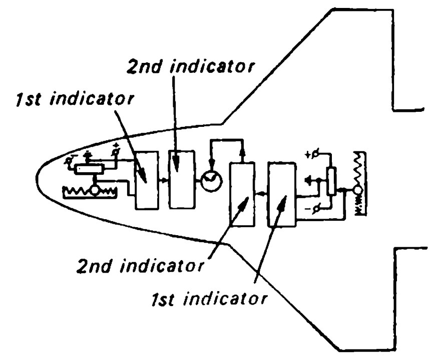


Fig. 72. The aircraft inertial system.

tude of the acceleration, it would be possible to compute the velocity that it would have after a certain time and the course that would be covered during this time.

In mathematics speed and course are determined by using the special operation: integration (summation).

By installing on a moving body (aircraft) a second accelerometer whose load is displaced not along the direction of motion but perpendicular to it it is possible to measure the acceleration acting in the transverse direction and with the help of a second integrator to compute the transverse deviation of the aircraft.

By electrically connecting every acccelerometer (longitudinal and transverse) with the indicator of the course covered (Fig. 72) it is possible with a part of integrators to read off at any time the distance covered from the starting point and the liner deviation from the initial direction of motion. In a geodesic system of coordinates[1] with the starting point of the aircraft

[1]The geodesic system of coordinates is usually a rectangular system of coordinates one axis of which coincides with the geodesic line: the shortest distance between two points on the surface of the sphere (earth). The great circle is the fragment of an arc of the circle passing through these points.

as origin this can indicate its position with respect to the given course line.

THE "MAN-MACHINE" RELATION PROBLEM IN AVIATION

A large number of instruments, signal lights, indicators of navigation systems and transducers of the flight regime are located on the instrument panel in front of the pilot. One might think the more the instruments the better, because more information reaches the pilot, which means that he knows more about how the flight is going and it is easier for him to take a decision if the situation in the air changes. However, it seems that this is not so at all.

The face is that the era of jet-propelled aviation began in the first post-war years and the flight speed and altitudes rose steeply. The nature of flight operation had been essentially changed by the middle of the 20th century. The creation of high-speed jet-propelled aircraft, the wide-scale application of airborne automated systems and the development of means of remote and centralized control led to a situation where the center of gravity of the operations to be carried out by the pilot shifted to the sphere of mental actions.

Furthermore, the designers sometimes have to create artificial mechanical loads on the steering wheel or control stick which disappear during operation so that the pilot can better feel the aircraft's responsiveness during flight. A heavy load was now placed on the nervous system of the pilot. Aircraft systems with their capacity for rapid action began to "demand" improved qualifications from the human being.

The problem of the struggle with psychological strain acquired great urgency. There arose the "man-machine" relation problem, i.e. the problem of reducing psychological strain by having the best (optimum) matching of man (pilot) and machine (aircraft control system).

Cybernetics came to the rescue. A new field termed "engineering psychology" was born. This science, a branch of cybernetics, makes it possible to explain the general principles of the engineering design of instrumental equipment and control systems taking into account the physiological capabilities of the human being.

As can be seen from Fig. 66, a pilot receives indicating information, converts it into controlling information and either delivers commands or himself performs certain controlling operations. The manual processing of the information (Fig. 73) mainly consists of three stages: reception of the information, grading and decision taking and putting the decision into operation. This division into stages, of course, is artificial since the pilot continuously pilots the aircraft. However, from the method point of view such a division of the control process is fully justified.

The task of engineering psychology is to ease the pilot's work in each

of these stages to the maximum extent.

During the first stage the pilot receives an exceptionally large quantity of information. As has already been noted, flight in a modern jet-propelled aircraft, and still more in a spaceship, is unthinkable without controlling numerous parameters. With the growing complexity and introduction of airborne systems of increased accuracy these parameters are multiplying. While at the dawn of aviation the pilot used to sense the air slipping by his cheeks and used to tie the altimeter to his knee (instrument panels did not exist) today there are so many indicators of flight regimes in the cockpit that sometimes they cannot be accommodated on the instrument panel. In many cases the designer is compelled to mount them even in the canopy of the cockpit.

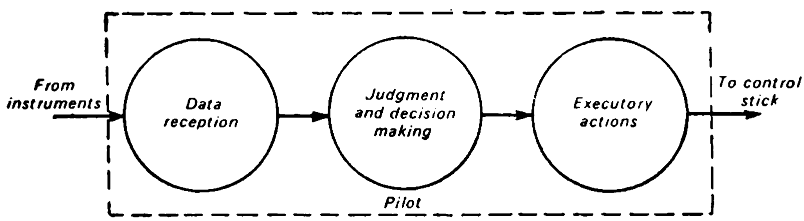


Fig. 73. Block-diagram of manual processing of information.

A large flow of information does not help the pilot at all, on the contrary it overloads his attention, disturbs him from carrying out his basic functions. The carrying capacity of a man exceeds by many times the amount of information that can be supplied to him on screens or boards. And still the pilot is not able to receive all the information supplied within the required time. The fact is that the information itself is supplied to the pilot in a crude, ugly form, in a "language" that a man can understand either badly or with an effort. Therefore the problem of working out a simple "man-machine language," i.e. working out an effective information code by which the moment-to-moment air situation or any other situation will be reflected simply and conveniently, like a mirror image, has become a very practical one.

One way to solve this problem is by the optimum location of indicators in the pilot's field of vision. It has been proved that a man's best reception is accomplished when he views the image at an angle of sight of $\pm 15°$. Therefore vitally important devices such as artificial horizon, course indicator and other indicators are located in the central part of the instrument panel according to their importance. Devices less important from the point of view of the final results are shifted to the outer edges of the panel viewed with peripheral vision at an angle of $\pm 25°$.

The data to read off can be presented in different ways. Most widely used are three types of devices: those with a movable indicator on a stationary scale, those with a rotating scale and a stationary pointer and those of the counter type. It was found that under identical conditions the errors in taking readings from the instruments with a vertical linear scale are 35%, with a semicircular one 16% and with a "window" type scale as on "ribbon" instruments (a movable dial moves past a stationary pointer located in a slit) only 0.5%.

It is known that a pilot cannot usually combine an accurate and fast quantitative estimate of a large number of separate readings of indicators and a qualitative assessment of the situation as a whole. In order to achieve this the idea of building integral (combined) instruments was suggested. In the simplest case it is an instrument with several pointers, each of which indicates one of a group of interrelated parameters. In the English system, in a fighter, for example, there are located on one scale the indicators of magnetic heading, azimuth, heading angle of the homing station, distance up to the beacon and certain other tactical parameters. The application of combined instruments leads to the reduction of the total number of indicator scales on the panel, a more compact grouping and a reduction in reading time.

Another method which is always useful (within the limits of carrying capacity) for reducing the movements of the eyes over the instrument panel and for generalizing the signals received in a common form is based on the special matching of scales and indicators of the instruments. The matching can be so done that while maintaining the given flight regime the pointers and indices of all the instruments would be set, for instance, in the "3 o'clock" position or along horizontal and vertical supporting lines (Fig. 74). In this figure the horizontal supporting line corresponds to the parameters that are varied during longitudinal control of the aircraft, i.e. "forward-backward" movement of the control stick and the engine control rod. Such parameters are: pitch angle, angle of attack, air speed, Mach number, vertical velocity, altitude and acceleration. To the vertical

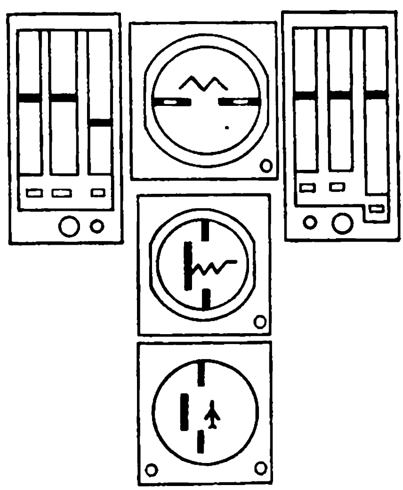


Fig. 74. Instruments with vertical and horizontal supporting lines.

supporting line correspond the parameters of lateral movement: bank angle, heading, angular velocity of yawing, and also certain parameters of the navigational and tactical situation.

A further increase in reception efficiency is achieved by the application of integral indicators which gave a "pictorial" description of the situation. Such indicators are called contact analogs or "conalogs" in foreign literature (Fig. 75). "Conalogs" in essence simulate the conditions of visual orientation and apparently create the effect of direct involvement. They can be either of the optico-electromechanical type or television type.

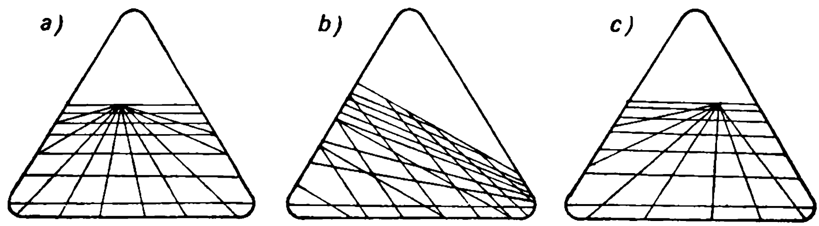


Fig. 75. Conalog:

a—horizontal flight along the axis of runway; b—flight with left bank and right-hand deviation from the axis of runway; c—horizontal flight with left-hand deviation from the axis of the runway.

In some models of "conalogs" of the first type the necessary flight information in the form of light signals is projected directly on the front portion of the cockpit canopy. In this case the pilot does not take his eyes away even for a second from the frontal hemisphere which is particularly important during the landing approach.

In another "conalog" the whole instrument panel is made up of two plane television screens. One of the screens, located vertically in front of the pilot, is covered with a transparent film of luminophore. In clear weather the pilot sees the ground in front of the aircraft through it, as through the glass of the canopy. In bad weather conditions this "window" is converted into a plane telescreen on which the image of the same ground is seen but now with the help of airborne radio means. Simultaneously information about the speed, altitude, heading angle and other parameters is given on this screen.

The second telescreen, 20 cm in diameter, is located horizontally in front of the pilot. On this an image of the ground being flown over by the aircraft is continuously shown and this image corresponds to the flight altitude. A point in the center of the screen shows the instant position of the aircraft. The concentric circles on the screen are used for the indication of azimuth, distance up to intermediate or terminal point of the route, available fuel, maximum distance that the aircraft can fly with the available fuel

taking into account the effect of wind, and so on.

The second stage of information processing by the pilot consists of grading it and taking a particular decision on this basis. In the second stage analysis and generalization of the information and the sequence of necessary operations to be carried out (on the basis of the criteria of importance known earlier) is determined; turning along the line of the given course, increasing the flight altitude, launching of airborne rockets, bombardment and so on. The psychological content of this stage includes the functions of nervous activity and the act of thinking.

So far comparatively little is known about the dynamics of operation of the brain, but now engineering psychology is already in a position to indicate the ways of constructing so-called directing (commanding) instruments which free the pilot from simple but tiresome and very often demanding individual judgments, logical operations and the operations of summation.

A directing flight instrument is apparently a combined instrument with one pointer. It shows what the pilot should do at the given moment, for instance, "Throttle-off," "Elevator-up," etc. The directing instruments find most wide application in the landing system.

The principle of operation of a directing instrument is based on the automatic analysis of readings of several flight instruments (artificial horizon, altimeter, rate-of-climb indicator, comparator of glide-path beacon) which is carried out by an airborne computer device according to the set program. Deviation of the pointer of the directing instrument is proportional to the sum (with its weight coefficient) of the magnitudes of the signals of pitch, altitude and rate-of-climb and to the deviation from the descending glide-path. By deviating the elevator the pilot tries to hold the pointer on zero. During this the actual pitching angle is being compared with the one determined by the computer device according to the magnitude of rate-of-climb of the aircraft and the deviation from the equisignal zone of the glide-path.

The third stage of the pilot's operation includes executive operations. During manual or semi-automatic flying the pilot himself moves the engine control rod, control stick (column), presses the pedals, switches apparatus on and off, i.e. carries out movement responses. These movements are themselves simple; however, the whole complexity of executive operations consists in their regulation from the central nervous system. The efficiency of even the simplest elementary movements is determined by a number of different factors: condition of nervo-muscular activity, experience of carrying out engine operations and so on.

The motor responses of a human being are understood better than the processes of reception and much better than the processes of decision taking. True, current research is distinguished by greater accuracy, by description of processes in the language of transfer functions and frequency character-

istics. This description of the human-operator is extremely important, for instance, for investigating the dynamics of guiding a fighter-interceptor and executing an accurate landing maneuver.

As a result of experiments it became possible to make a dynamic scale model of a pilot in a control loop (Fig. 76). According to foreign specialists this model reproduces within an accuracy of 85–90% human behavior in the region of low frequency signals. As is seen from the figure, a man as an element in the control loop can be schematically represented by a series connection of four linear and two nonlinear components.

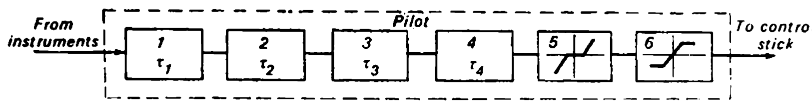


Fig. 76. Dynamic scale model of a pilot:

1—delay component; 2, 4—inertia components; 3—booster component; 5, 6—nonlinear components.

The first component characterizes the process of observing the instrument readings. It is followed by a delay of a constant time interval τ_1. The second (inertia) component describes the process of taking a decision. The third (booster) component shows that it is in the nature of a man to regulate not only according to the deviation, but also according to the rate of change of this deviation, apparently superseding (augmenting) the course of events. The fourth (inertia) component describes the process of nervo-muscular interaction on the control stick, and the fifth and sixth components characterize the non-linearities in human nature: the pilot does not respond to very weak signals, while in the case of a rather strong error signal he tends to maintain the constant rate of liquidation of the error.

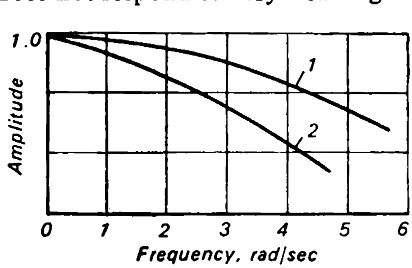


Fig. 77. Amplitude-frequency characteristic of the pilot:

1—before start; 2—in flight.

Fig. 77 represents the amplitude-frequency characteristic[1] of a pilot before the start of and while carrying out responsible flight assignments. From a comparison of the characteristics it is easy to see that in flight the quality of signal tracking worsens even in the range of comparatively low frequencies.

The executive actions of the pilot in aircraft control must require, like

[1]Amplitude-frequency characteristic is the graphical dependence of amplitude of the output signal on the frequency of the input signal. In the given case the man is taken as a low-frequency filter having one inlet and one outlet.

all the preceding operations, the minimum amount of time. Therefore it is clear that the control members (control stick, engine control rod, buttons, steering wheels, tumbler switches) must be within the anthropological tolerances, i.e. they must be made to suit the "movement" characteristics of the human being.

AUTOPILOT: SIMPLE AND SELF-ADAPTING

It has been related above how with the help of the methods and resources of engineering psychology the conditions of flight labor are eased: control sticks are made to fit the hand snugly, instrument scales have the relevant shape and color, information about flight parameters contains no mistakes—it is extremely compact and the pilot need not see all the indicators on the instrument panel every time. This however is not enough. Engineering psychology does not free the crew from tiresome, though simple, physical loads. During flight in bumpy weather over thousands of kilometers the pilot gets very tired of monotonous control operations. And controlling is necessary as the atmosphere is never calm and quiet and "strives" to carry the aircraft away from the set course or flight level. In order to free the pilot from this monotonous and tiresome work an autopilot is used.

The autopilot is an automatic control machine which in certain stages of flight replaces the pilot, gives him the opportunity to relax (for instance on civil aviation aircraft) or to carry out more important functions than simple flying (for instance, pinpoint bombing, reconnaissance or firing on an airborne target).

Usually the tasks of an autopilot are to stabilize (to maintain at a constant level) the course, yaw and pitch angles. There are autopilots that perform more complicated functions too.

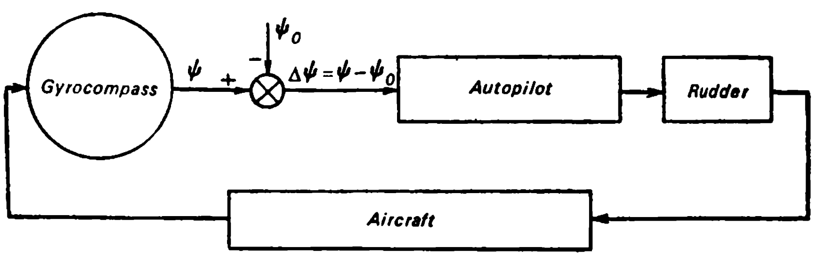


Fig. 78. Stabilization of course with the help of an autopilot:

ψ_0—set course; ψ—actual (instant) course.

Let us look at the operation of a typical autopilot in automatic stabilization of the course angle (Fig. 78).

The basic elements of the course channel of an autopilot are the course

gyroscope (sensing element), amplifier and servomotor (steering engine).

If the aircraft flies exactly along the set course the autopilot does not operate, to be more accurate it does not give signals to the aileron. However, as soon as the aircraft goes off course even slightly it is momentarily "noticed" by the course gyroscope.

How does this happen? While turning off course the aircraft turns about the vertical axis. Together with the aircraft the rigidly fixed casing of a potentiometer also turns. But the brush of the potentiometer connected not with the aircraft frame but with the gyroscope remains in place (due to the basic property of a gyroscope to preserve the set attitude). Thus the brush is displaced with respect to the potentiometer and electrical voltage is generated between the brush and the central point of the potentiometer. This voltage is amplified in an electronic amplifier and actuates an electro-hydraulic valve in the booster. As a result the steering engine (in this case the booster) operates and adjusts the aileron in such a way that the aircraft returns to its set course. Thus the aircraft returns automatically, without the pilot's efforts, to the set course.

Actually the operation of an autopilot is considerably more complicated. In order to get rid of aircraft vibrations while returning to the set course it becomes necessary to introduce special dumping "buffer" devices augmenting correcting circuits, local two-way and cross communications and many others.

Recently so-called "self-adapting" autopilots have been mounted in the new, superbly maneuverable high-speed aircraft. By their appearance they are bound to cause the further development of one of the basic sections of cybernetics—the theory of adaptive (adjusting) systems. Adaptive cybernetic systems in essence simulate one of the fundamental properties of the biological organism: adaptation (adjustment) of its characteristics with changes in the environment. As a result even if the environmental conditions are changed in the most unfavorable manner the efficiency of the system does not change. The systems for regulating the pressure and temperature of the blood in the human organism can serve as examples of biological adaptive systems.

Let us assume now that a jet-propelled aircraft equipped with a simple autopilot is flying in the stratosphere. With a rapid gain of height the density of air quickly drops and so does the efficiency of the aerodynamic controls. The aircraft becomes "dull" in control. The amplification factor (transfer factor) of the autopilot adjusted for medium altitudes proves to be too small for the new conditions and control efficiency decreases.

Where is the way out? It is possible to do it this way: to provide the autopilot with a special correcting circuit which would automatically take into account the variation of flight speed and altitude (Fig. 79). Depending on the variation of dynamic head the amplification factor k of the auto-

pilot is automatically readjusted. The amplification factor k increases as many times as the magnitude of dynamic head decreases. The efficiency of the controls does not decrease. In this way a self-adaptive autopilot is obtained. Autopilots of this type used abroad are self-adaptive autopilots with passive (or open) self-adjustment circuits.

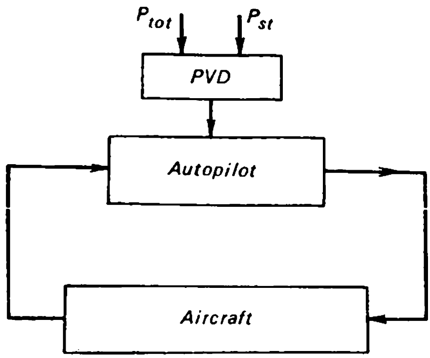


Fig. 79. Autopilot with open self-adjustment circuit.

In spite of the simplicity of construction this kind of autopilot has essential drawbacks. These arise from the fact that the self-adjustment circuit is not a closed one, i.e. apparently the instrument first has to measure the unfavorable factors acting on the system of flight control and then artificially compensate for them. But can all the disturbing factors be measured? Of course not. Indeed, the efficiency of the aerodynamic control depends not only on the dynamic head but also on the centering of the aircraft, which in turn changes with the rate of fuel consumption, with the launching of airborne rockets and dropping of fuel tanks, and also due to neighboring air currents, atmospheric turbulence and many other factors. Therefore on modern high-speed jet-propelled aircraft abroad autopilots with closed self-adjustment circuits (Fig. 80) find wind-scale application.

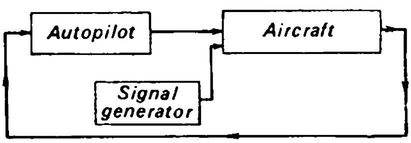


Fig. 80. Autopilot with closed self-adjustment circuit.

It can be seen from the figure that the autopilot's circuit is supplemented with a special signal generator. This generator produces probe (main) electric pulses which are fed to the steering engine. The electrical pulses have a rectangular shape and a repetition frequency of nearly 4–6 Hz. Such pulses are practically unnoticeable for the pilot but they pass through the aircraft. The reaction of the aircraft to such impulses can be measured by the rate gyroscopes. As a result, continuous information about the efficiency of aerodynamic controls is available aboard in flight. The system is so adjusted as to hold the amplification factor k to its maximum level.

Evidently to increase the factor k above all possible values is to destroy the stability of the control system and the free vibration phenomenon which is dangerous for technical devices comes into play. Therefore at the very first symptoms of free vibrations the factor k is decreased and the free

vibrations vanish. Thus the self-adapting autopilot provides the maximum efficiency of aerodynamic controls.

AIRBORNE ELECTRONIC BRAIN

Until recently both control and adjustment of automatic aircraft systems were accomplished by the pilot himself. However, due to overloading and also to definite physiological limitations (fatigue, low speed of reaction, etc.) the crew could not achieve the maximum efficiency of operation of aggregates while carrying out flight assignments. The use of mathematical machines aboard, however, makes possible an essential improvement in the tactico-technical characteristics of fighter aircraft by means of complex automation of flight and battle operation control.

Continuous operation computers which, in essence, are the physical model of the processes inherent in the problem to be solved have been described above. Every physical quantity involved in the problem to be solved (for instance, distance to the target, aircraft speed, its altitude, lead angle) is represented by another corresponding quantity in the model (for instance, electric voltage, angle of rotation of shaft, speed of the electric motor). The limits of variation and the scales of quantities are chosen on the basis of the conditions of the problem. However, continuously operating computers possess a fair number of basic drawbacks. They can be listed as follows:

1. Accumulation of error during computation.
2. Close dependence of construction on the aim of the device (a computer designed for fire control cannot easily be adapted to solve navigational problems).
3. Dependence of accuracy on the size. An increase in accuracy, generally speaking, requires an increase in scale, which leads to increases in the sizes and weights of components. In practice the actual attainable accuracy is only 0.2%.
4. Complexity of production. For continuous operation highly accurate potentiometers, gear wheels, eccentrics, etc. are required. These are costly and complicated to build and assemble. Therefore the aircraft analog computers continue to take second place to digital computers.

These machines operate with interrupted, quantified signals. It is known that any physical quantity of the problem to be solved can be not only compared with another physical quantity but also expressed by a number written in a certain number system in the form of many digits. Instead of the universally accepted decimal number system in digital computers the so-called binary system of Leibniz is usually used to represent a given physical parameter. In this system there are only two symbols: 0 and 1.

The binary system sets a simple bond with the modern pulse technique

("1"—there is pulse, "0"—there is no pulse) and thereby provides an exceptionally fast rate of performing computational operations.

Naturally the binary system is compared with the Morse code in which the digits, letters and indeed the whole message can be conveyed by a proper combination of dots and dashes. The basic elements of the digital computer are cells. These are electronic flip-flop relays which must be in one of two conditions: "On" or "Off". Thanks to the electronic circuit, digital computers possess a large carrying capacity and are capable of performing tens and hundreds of thousands of operations in a second.

Apart from the unusually rapid operation of digital computers the following merits can be credited to them:

1. No loss of accuracy during operations irrespective of the number of operations.

2. Versatility. One and the same digital computer can solve both navigational problems and the problems of fire or bombing control without any substantial increase in weight or complexity. It is possible, for instance, to use a digital computer at the start of flight for navigational purposes, then to switch over by pressing buttons to carry out interception or bombing tasks and then to return to navigational problems.

3. Manufacturing simplicity. Digital computers are made of a large number of identical components, which are easily adapted to production on conveyor belts.

4. Potential high reliability. When simple and durable semiconductor triodes and integrating circuits totally replace electronic valves, which are occasionally used in computers even now, their potential reliability will be 100%.

5. Ability to perform logical operations by analyzing intermediate results and to choose the best method of solution, which is very important in connecting up a digital computer with the airborne control loop (autopilot, automatic equipment of power plant).

The basic elements of a digital computer are internal and external memory units, an arithmetic unit and the control unit (Fig. 81). The external memory unit (non-volatile memory) accommodates the data on the basis of which the operations are to be carried out and the so-called program, which is a set order of arithmetical operations in the form of coded signals. To store information punched cards, punched tapes, magnetic tapes and magnetic drums are used.

In order to achieve instantaneous calculation of the required data the groups of numbers are automatically fed with the help of signals to the internal memory unit (internal storage) from where they can be conveyed to the central arithmetic unit in a millionth of a second. In the internal memory unit the "words" are preserved in the form of a binary configuration in memory registers numbered in order. To store the information

memory units on magnet poles, magnet drums and magnetic relay lines are used, guaranteeing minimum access delay.

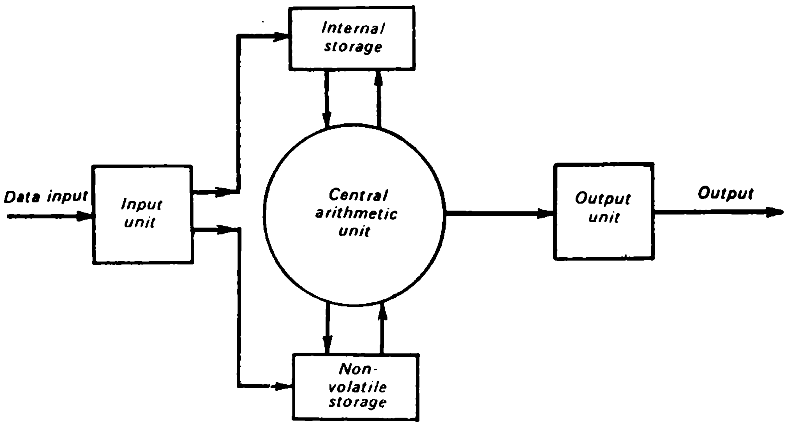


Fig. 81. Principle scheme of a digital computer.

In the central arithmetic unit not only four basic arithmetic operations (addition, subtraction, multiplication and division) are carried out but also integration, differentiation, extraction of root and so on.

The control unit is used to control all the machine's components in conformity with the signals of the program fed into it.

The results of calculations are extracted from the internal storage through the output unit to the computer output. After this the results must be decoded and again transformed into readable form or transmitted to the control loop of the automatic systems of the aircraft.

The sequence of operations, including the transmission of data between individual memory units as well as between the internal storage unit and the central arithmetic unit and also the logical selection of one or more intermediate results is accomplished with the help of the program. For every problem it is the specific order of signals which are "read" and carried out by the machine.

An American firm has constructed a small-sized aircraft computer to operate with a ground hyperbolic radio-navigational system and also to make fire control computations. The flight altitude, course and true airspeed of the aircraft are fed from the airborne flight instruments in continuous a pattern.

The converters of continuous quantities into digital ones are the continuous readers which choose input quantities on receiving signals from the computer. Every input quantity is checked by a special logical device in order to determine before use whether it is suitable. In case of unsuitability

of a certain quantity it is thrown out and its magnitude, measured earlier, is fed into the computer.

The computer is designed taking into account its conjugation with the control loop of the autopilot. Conversion of the control signal into the angular displacement of the rotor of a differential syncho is accomplished by means of a special impulse counter, consisting of seven cells. The pulses are delivered to the counter every 0.5 sec irrespective of whether the counter has counted up to zero or not. Due to this, false control signals, large in magnitude but of short duration, do not influence the autopilot. In order to achieve fast input of a large course correction into the autopilot and control safety during small course corrections the frequency of pulses of the driving oscillator is automatically varied in proportion to the magnitude of the control signal.

New opportunities are opening up for aircraft digital computers on the introduction of the latest achievements in technology in the fields of chemistry, electronics and molecular physics. The use of printed circuits and micro-components not only reduces the weight and size of the computer but also increases the rate of action and accuracy of delivery of the necessary information. It also considerably improves the operation of airborne automatic systems.

The modern computer consists of hundreds and thousands of different micro-components. Failure of any of its tiny elements can cause the whole system to go out of order. A foreign firm has worked out an automatic unit with program control meant for preflight checking of aircraft radio-electronic apparatus. Its basis is the airborne digital computer.

If any fault or variation in the parameters of certain components that could cause failure of the aircraft control system is detected the computer gives a sound signal and automatically switches off the defective blocks. Then the unit itself selects from the photographic library placed in it a suitable frame and projects it on a screen where the necessary element to be replaced or repaired is indicated by a deep red arrow.

In the ideal case the problem of reliability would have approached its solution had it been possible to create a cybernetic complex according to the principle of so-called active reservation. In this case any defect that arises is compensated automatically by a change in the structure of the circuit itself as happens in the case of damage to biological organisms. In this direction cybernetics has achieved some success. In the well-known cybernetic unit Eschbee-homeostat partial breakage and even damage to 22% of all connections have not caused any major damage to the functioning of the system.

Many complicated problems are involved in the practical realization of an airborne cybernetic complex perfect in all respects. However, all of them will be solved. It is only a question of time.

SECTION SEVEN

Astronautics

PORTENTS OF SPACE FLIGHT

Human flight in space appears to be the acme of scientific and engineering progress at present.

Writing appreciatively of the grandeur of outstanding scientific feats by pilot-astronauts, Academician A.A. Blagonravov said:

"...space flight is the feat not just of one man. It takes creative search, strenuous labor by tens of thousands of people. It embodies a high level of many fields of Soviet science and engineering... Spaceships and launching vehicles are essentially a bunch of achievements of modern science and engineering..."

The creation of space rockets was evidently the result of tenacious, selfless and inspired labor by enthusiasts of interplanetary flights and in the first instance by enthusiasts of rocket engineering. Even now, in the years of greatest success in mastering cosmic space, it is quite interesting to know how rocket engineering was born in the Soviet Union.

Theoretical principles of rocket engineering

The most important contributory factor in the success of Soviet rocketry was the proper choice of direction of scientific research and thorough theoretical study of the problems of rocket engineering.

The theoretical foundations of rocket propulsion and astronautics were laid in the works of K.E. Tsiolkovskii at the turn of the century. His work of genius, "Investigation of Outer Space by Jet Devices," published in the journal *Scientific Review* No. 5, 1903, opened a new chapter in the archives of human learning: the science of exploration of cosmic space by human beings.

Outstanding books by Soviet scientists have played a very important role in the development of rocket propulsion and ideas of astronautics. In mentioning the works of K.E. Tsiolkovskii it is necessary to add that his books not only brought this knowledge to wide circles of scientific and technical society but also performed a large organizational function. By publishing his correspondence with numerous enthusiasts in his books Tsiolkovskii promoted acquaintance and intimacy between people interested in the problem of interplanetary communication.

At the end of the 20s and at the beginning of the 30s of this century Prof. N.A. Rinin's work *Interplanetary Communications* in nine volumes was released in Leningrad. This book was a genuine encyclopedia of astronautics in which the history of the problems of interplanetary communications and all the theoretical work on jet propulsion and astronautics known at that time were presented.

Later Y.V. Kondratyuk's *Conquest of Interplanetary Space*, F.A. Tsander's *Problem of Flight by Jet Vehicles*, M.K. Tikhonravov's *Rocket Engineering*, S.P. Koroleva's *Rocket Flight in the Stratosphere*, G.E. Langemak and V.P. Glushko's *Rockets, Their Construction and Use* and A.A. Shternfel'd's *Introduction to Astronautics* were published. In these books many interesting ideas were set forth, some of them still valid.

The contribution of Soviet scientists to the development of the theoretical principles of rocket engineering and astronautics is so significant that it deserves treatment on the same level as experimental works on the construction of rocket engines and rocket flying vehicles.

The great merit of the Soviet scientists who worked out the problem of space flight is that in the first place they concentrated their attention on the base of this problem, which is rocket energetics. Even K.E. Tsiolkovskii raised the problem of development of rocket energetics in his works.

Sources of energy

The source of energy for the working of a rocket engine is fuel. That is why K.E. Tsiolkovskii in his earlier works on jet propulsion raised the problem of fuel as one of the main ones. To him belongs the idea of creating a rocket engine working on liquid fuel which is more advantageous from the energy point of view than the powder used at that time. Tsiolkovskii suggested a number of interesting ideas in the theory of fuels for rocket engines. Many of these ideas have already been put into practice, others await application. For instance, Tsiolkovskii proposed to use hydrogen as the combustible and oxygen and ozone as oxidizers in rocket engines.

The students and followers of Tsiolkovskii further developed his ideas. Y.V. Kondratyuk proposed to use high-calorific boron-hydrogen compounds as combustible in rocket engines. In the gas dynamics laboratory in

1930 it was for the first time proposed to use nitric acid, nitrogen tetroxide, hydrogen peroxide, hydrochloric acid, tetranitromethane and their solutions in each other as oxidizers for rocket engines. Soviet scientists suggested and substantiated the valuable idea of using in rocket engines not only the reaction of oxidation but also other exothermic reactions, i.e. those accompanied by the extraction of heat, for instance, the reaction of compounding with fluorine which is characterized by a stronger exothermic effect.

A highly fruitful idea was suggested by Y.V. Kondratyuk and F.A. Tsander who proposed to use in rocket engines, in addition to the liquid fuel, a metallic one, which increases the thermal effect of the reaction. This idea is also interesting because it points to the possibility of using the metallic parts of the rocket that become unnecessary, for instance empty fuel tanks, as fuel.

Creation of the theory of fuels for rocket engines is the outstanding achievement of the Soviet school of rocket engineering. Maximum thermal (calorific) effect is not the only essential of rocket engine fuel. The working capacity of a gas depends on its temperature, pressure and specific volume. Consequently it is essential that the products of fuel combustion not only have high temperature, but also as large a volume as possible or, more accurately, minimum molecular weight. Also important are such fuel characteristics as storage and operational safety, cost and possibility of mass production. All these questions were thoroughly worked out by Soviet scientists, who created the fundamental theory of fuel for rocket engines. Outstanding research in this field was set forth in the book *Liquid Fuel for Jet Engines* by V.P. Glushko, published by the N.E. Zhukovskii Air Force Academy as long ago as 1936.

In this major work, which is an indisputable authority on rocket engineering, the following proposition was made: "The question of efficient fuel is of paramount importance. Before beginning to work out a jet engine it is essential to choose the most suitable fuel, i.e. oxidizer and combustible. The quality of the engine developed, and sometimes the success of the whole project, depends on how suitable this choice was."

A large contribution to the theory of fuel for rocket engines (propellant) was made by Doctor of Technical Sciences N.G. Chernishev.

The results of interesting research dedicated to the problem of creating rocket engines and choosing a propellant for them have been published in two publications *Jet Propulsion* and *Rocket Engineering*.

The correct scientific formulation of work in the field of rocket engineering and concentration on questions of rocket energetics enabled the scientists and designers of the USSR to create high-quality engines working on effective propellants. This served as the basis for the remarkable success of Soviet rocketry.

Accuracy of flight

Among all the problems of astronautics the next most important problem in rocket engineering is the accuracy with which the rocket is placed in a given orbit. For this purpose it is necessary to have at our disposal methods of precise calculation of the active part of a rocket's flight. This task belongs to the questions of dynamics of the rocket, i.e. rocket dynamics, the basis of which is the mechanics of bodies with variable masses. Just as aerodynamics served as the theoretical foundation for the development of aviation rocket dynamics serves as the theoretical basis of rocket engineering. Therefore the development of rocket dynamics is the most important condition for the achievement of space flight.

The role of rocket dynamics is not only to carry out accurate calculation of rocket motion. Investigation of the equations of rocket motion makes it possible to find the optimum flight regimes whereby placing a rocket vehicle in orbit is accomplished with minimum loss of energy. Thus the investigation of rocket flight dynamics is directly connected with the problem of rocket energetics. An integrated solution of these problems to a considerable extent determines one's success in mastering space.

The task of calculating the active trajectory of a rocket's flight consists in integrating the equations of its motion. This task is analogical to the fundamental problem of external ballistics but is considerably more complicated because, unlike a shell, the thrust force acts on the rocket and besides this its mass becomes a variable quantity due to the consumption of fuel.

The fundamentals of mechanics of bodies of variable mass were worked out by Professor I.V. Mescherskii. In 1897 he established the basic equation of motion of a point with variable mass. This equation is a matter of principle in the history of theoretical mechanics and particularly in rocket dynamics. From Mescherskii's equation, as a particular case with constancy of mass, Newton's second law follows. This holds good only for material points having constant mass.

In the same years K.E. Tsiolkovskii carried out mathematical research on rocket motion. He created the fundamental theory of jet propulsion. In his outstanding work *Investigation of Outer Space with Jet Devices* the equation of rocket motion which transforms a complicated physical concept (rocket flight) into exact mathematical language was deduced.

Tsiolkovskii's equation

$$V = W \ln \frac{M_0}{M_k}$$

establishes the dependence of velocity V which the rocket assumes on exhaust velocity of gases W, initial mass of rocket M_0 and the final mass of the rocket, M_k, i.e. the mass of the rocket after consumption of fuel. This equation of rocket motion acquired the name "Tsiolkovskii's formula."

The above equation describes the flight of a rocket in free space, i.e. beyond the atmosphere and far from large celestial bodies that might attract it.

While developing K.E. Tsiolkovskii's work Soviet scientists considered various cases of rocket flight in the gravitational field either of the earth or of other celestial bodies and deduced 15 different forms of the equation of rocket motion—15 "Tsiolkovskii's formulas."

The work on bodies with variable mass and theory of jet propulsion was developed in the Soviet Union especially in the 30s of this century. Much work was done on this problem by F.A. Tsander, who worked out the dynamics of ballistic missiles and popularized their application for supersonic transport of civil cargo.

An important chapter in the theory of jet propulsion was worked out by V.P. Vetchinkin. He created the dynamics of winged jet vehicles. His remarkable investigations are published in the collections of papers *Jet Propulsion.*

In the same collection of papers there are other interesting works, for instance in collection No. 1 we find L.S. Dushkin's detailed paper "Fundamental Tenets of the Theory of Jet Propulsion," in collection No. 2 L.S. Zuev's work "On the Vertical Flight of a Rocket."

It is necessary to note here the talented work of Y.V. Kondratyuk on the theory of flight in outer space: *Mastering of Interplanetary Space* which was published in 1929. It was a valuable contribution to the theory of interplanetary communications and rocket dynamics. In this book the application of K.E. Tsiolkovskii's equation to multistage rockets was investigated, including ones with an indefinite number of stages, i.e. with continually jettisoned empty tanks.

In his book *Introduction to Astronautics*, published in 1937, A.A. Shternfel'd gave the solution of a number of interesting problems of rocket dynamics.

Exhaustive and interesting research on the mechanics of bodies with variable mass was carried out by Professor A.A. Kosmodem'yanskii and his students. The mechanics of bodies with variable mass originated by Mescherskii and Tsiolkovskii and developed in the works of Soviet scientists is one section of the theoretical basis for rocket engineering.

Law of supersonic flows

In order to make accurate calculation of rocket motion it is essential to know the forces acting on it, including those of the air acting on the rocket body during the part of its flight through the atmosphere. Exact determination of air drag is necessary for correct calculation of the active portion of the flight of space rockets. Consequently aerodynamic research plays an important part in solving problems of the exact calculation of rocket boosting.

Since the speeds of space rockets exceed that of sound by a number of times, there is needed for calculation of their motion the development of the section of aerodynamics that is known as the aerodynamics of supersonic flows. This section, which has been developed over the past ten years, has become an independent branch of science called gas dynamics.

The role of gas dynamics is not limited to determining the drag forces of air. Gas dynamic research is oriented toward evolving the best aerodynamic shapes of flying vehicles in order to bring down to a minimum the drag force they undergo during acceleration.

To the lot of gas dynamics also falls development of the best external shapes for a rocket's control members: the air control surfaces, if any, or gas control surfaces, i.e. Tsiolkovskii's vanes if control is accomplished with their help.

One should note that apart from research on the external shape of rockets, during the design stage one has to solve a number of gas dynamic questions concerning the engine, for instance, to calculate the flow of gas through the nozzle or flow part of a gas turbine of a turbo-pump aggregate.

In summary it can be said that in designing a rocket there arises a considerable number of gas dynamic problems where successful solution exerts a critical influence on the achievements in the field of rocket engineering.

In order to design a supersonic flight vehicle, to determine the lift of a wing, to ensure the reliable operation of a control member and to compute the forces acting on it, it is necessary to learn the laws of motion of bodies in a gas at supersonic velocities or, which is the same thing, the laws of flow of a supersonic stream of gas past the bodies situated in it.

The peculiarities of the motion of air or any other gas at velocities greater than that of sound had been shown in the works of an outstanding Russian scientist, S.A. Chaplygin, as early as 1902. His masterpiece *On Gas Jets* was used as the basis for the science of motion through gas at supersonic velocities.

Gas dynamics, originated by S.A. Chaplygin, began to develop rapidly in the 30s. Many scientists the world over, including the Soviet scientists: Academicians N.E. Kochin, M.V. Keldish, B.S. Stechkin, S.A. Khristianovich, A.A. Dorodnitsin, G.I. Petrov, Professor F.I. Frankel and others published works on the subject. Soviet aviation and rocket engineering thus had ways to calculate the forces acting on a body in a supersonic airstream, making possible the choice of the most favorable shapes for supersonic flight vehicles. The successful works in the field of gas dynamics made it possible to work out the flow part of rocket engines.

Thus the cardinal questions that served as the basis for the development of rocket engineering, i.e. the problems of rocket energetics, rocket

dynamics and gas dynamics were solved in the works of Soviet scientists. The successful solution of these problems served as the theoretical foundation for the present achievements in conquering space.

The three tasks already noted: reaching the set velocity, provision of high accuracy in placing the space rocket in orbit and solution of a complex of gas-dynamic problems that will guarantee accomplishment of the first two tasks are basic to rocketry.

Simultaneously with the solution of these problems Soviet scientists worked on the development of many other fields of science and engineering contributing to the success of rocket construction. Of prime importance here is the work in the field of metallurgy. Research in the theory of elasticity and the strength of materials has also played a large role.

The role of the work of Soviet scientists in automation and telemechanics proved to be exceptionally important. As is known, the automatic equipment mounted in the rocket must guarantee its motion strictly according to the calculated trajectory. The flight of the automatic (space) station Luna-16 can serve as an example of the amazing operational accuracy of automatic equipment.

We may also note the large number of scientific and technical problems that Soviet scientists worked to solve at the beginning of the development of Soviet rocket construction.

Birth of rocket engineering

From its very birth Soviet rocket engineering involved the whole of society. A large number of scientists, designers and inventors made their contribution to its development. Scientific popularization of the ideas of astronautics and rocket engineering, experimental investigation and experimental design projects in the field of rocket construction were carried out by many scientific organizations in the country.

In the N.E. Zhukovskii Air Force Academy in Moscow a section of interplanetary communications was organized as far back as 1924. This took as its aim the popularization of the problem of interplanetary communications, organizing laboratories to design and test rocket engines and preparing for the publication of the journal *Rocket*.

K.E. Tsiolkovskii heartily supported the work of this section. In his letter of April 29, 1924, the scientist wrote: "Dear friends, I am happy at the opening of the section of Interplanetary Communications. . ."

In May, 1924, the section was converted into the Society of Interplanetary Communications Studies. The Society of Interplanetary Communications Studies existed only for a short time but played a positive role in popularizing astronautics and rocket engineering. "The main service of the Society," wrote its chairman G.M. Kramarov, "was that as far back as 1924 it united the strength of many talented engineers, designers and in-

ventors interested in interplanetary communications. . ."

In the spring of 1927, to mark the 10th anniversary of the October Revolution and K.E. Tsiolkovskii's 70th birthday, the first international exhibition of models of rockets and interplanetary vehicles prepared by scientists of various countries was organized in Moscow.

In the exhibition hundreds of schemes, diagrams, pictures and models reflecting the works of K.E. Tsiolkovskii, F.A. Tsander, R. Esno-Pel'try, G. Obert, Maks Vale, N.A. Ranin and many others were displayed.

A very large part in popularizing the scientific basis of astronautics and rocket engineering, in making astronautics a science, in recognizing the need to set up rocket construction projects, was played by the lectures and published articles of a large number of Soviet scientists, among whom Prof. V.P. Vetchinkin, F.A. Tsander, Y.V. Kondratyuk, Prof. N.A. Rinin and K.L. Baev are in the first rank.

The role of K.E. Tsiolkovskii himself is particulary great in this patriotic labor. We judge this man highly as an outstanding scientist, the creator of the theory of rocket propulsion, founder of the science of interplanetary flights and founder of jet-propelled aviation. Perhaps the largest recognition should go to Tsiolkovskii's own wholehearted struggle for the triumph of the ideas of astronautics.

The theoretical investigations of K.E. Tsiolkovskii and of those native and foreign scientists who developed his works and the wide support for the ideas of astronautics by Soviet scientific society had an important role in organizing practical projects in the field of rocket engineering in the USSR at the end of the twenties.

The main decisive factor that conditioned the birth of Soviet rocket construction was the policy of the party to industrialize the country, which enthused the entire Soviet people for the struggle for technical progress.

In 1928, the Gas Dynamics Laboratory (GDL) was organized by the military scientific research committee of the Revolutionary War Council of the USSR in Leningrad. In the GDL the group of scientists: N.I. Tikhomirov, B.S. Petropavlovskii, G.E. Langemak, V.A. Artem'ev and others continued work on the creation of rocket engines, and on a high-quality solid fuel that had begun in Moscow as far back as 1921.

In May, 1929, on the initiative of V.P. Glushko, a section for electric and liquid-propellant rocket engines was organized in the GDL and began theoretical and experimental research. In this section the first native rocket engine (ORM–1), working on nitrogen tetroxide and toluene, was designed in 1930 and constructed in 1931.

In 1931 one more experimental engine was prepared at the GDL and numerous tests were carried out on these engines. In the same year the ORM–2 engine was worked out and built.

The labor of the collective of the GDL played a decisive part in the cre-

ation and development of liquid-propellant rocket engines in the USSR. From the portals of the GDL emerged specialized personnel who built the powerful rocket engines for Soviet space rockets.

In 1929, one of the pioneers of Soviet rocket construction, F.A. Tsander, began work in the Central Aero-hydrodynamic Institute on experimental research into the processes taking place in jet engines. In 1930 he built for this purpose a model of the jet engine OR–1 working on benzine and compressed air. The test carried out on this model enabled F.A. Tsander in 1932 to design and construct the liquid-propellant rocket engine OR-2 which used benzine and liquid oxygen as fuel.

In 1929 the theory of air-breathing jet engines currently used as the basic energy source for transonic and supersonic aviation in all countries of the world was worked out in the Soviet Union.

In 1931, in the bureau of air engineering of the Central Council of Osoaviakhima, on the initiative of F.A. Tsander, S.P. Korolev and other enthusiasts of astronautics, the group for jet propulsion studies (GIRD) was organized. S.P. Korolev was appointed as director of the GIRD. Organizers, guides and leading scientific workers of the GIRD were S.P. Korolev, M.K. Tikhonravov, Y.A. Pobedonostsev, A.N. Polyarnii, E.S. Schetnikov, L.S. Dushkin, M.S. Kisenko and others. Similar groups began to appear in other cities too. Parallel with the Moscow group the Leningrad group, the LenGIRD, headed by V.V. Razumov, worked most successfully.

In the first months of their operation the GIRDs dealt with popularizing rocket engineering, collecting and uniting specialists interested in this problem. Soon the Moscow group, which was the biggest and most successful, was named the TsGIRD.

In April, 1932, a production and experimental GIRD base was established in Moscow. This was the first scientific-research center of rocket construction in the world. It was situated on Sadova-Spaskii street.

Here for the first time in the Soviet Union work on the construction of rockets with rocket engines was started. The rockets built in the GIRD appeared to be heralds of the grand victories of science in conquering outer space.

The organizer and leader of the GIRD was Sergei Pavlovich Korolev, the future constructor of space rocket systems with whose help the first artificial earth satellites were launched and the first spaceships were put into orbit.

This scientific genius brought such a large contribution to the development of astronautics that his name can be rightfully placed in the same rank as the names of the great scientists, Lomonosov, Mendeleev and Tsiolkovskii.

S.P. Korolev's life is a bright example of selfless service to the motherland, a great achievement of idea and labor. The socialist motherland highly

appreciated the services of Sergei Pavlovich Korolev. He was elected as academician member of the presidium of the Academy of Sciences, USSR. The title of Hero of Socialist Labor was conferred on him, and later he was rewarded with a second medal, the Golden Star.

At the end of 1933 the amalgamation of the group of jet propulsion studies and the gas dynamics laboratory took place and on this base in Moscow was established the jet research institute which now began its fruitful activities.

It is necessary to note here a highly important circumstance, the organization of systematic training of specialists in rocket engineering in the USSR at the beginning of the 30s. Thus in 1932 on the initiative of S.P. Korolev special courses for design engineers in rocket engineering were organized in Moscow. In this original shortlived institute lectures were delivered by prominent Soviet scientist-specialists of GIRD and the RNII: Professors V.P. Vetchinkin, B.M. Zemskii, A.N. Zhuravchenko, V.V. Uvarov, B.S. Stechkin, engineers M.K. Tikhonravov, V.P. Glushko, Y.A. Pobedonostsev and others. The leaders of the GIRD had by this time already made the accomplishment of human flight in space their aim. Therefore a course on the physiology of high altitude flight was included in the program.

In the same years, on the initiative of Professor K.A. Putilov, a department of gas dynamics was organized in Gorki University as one of the theoretical bases of rocket engineering. The training of rocket specialists was also carried on in other educational institutions.

First Soviet rocket engines

The engines of the space rocket that put the satellite *Proton* into orbit developed a thrust of 60 million hp. It is interesting to look at the sources of Soviet rocket engine construction as the heralds of modern liquid propellant rocket engines.

Soon after the first native liquid-propellant rocket engines a series of subsequently perfected experimental engines was created in the GDL. In 1932 the designs of the engines from ORM–4 to ORM–22 were worked out, in 1933 those from ORM–23 to ORM–52.

Fifty-two designs of rocket engines in two years ! The ORM–50 engine with a thrust of 150 kg, and the ORM–52 with a thrust of 300 kg, working on nitric acid and kerosene, underwent official static tests in 1933.

From 1931 the pressure system for the delivery of the components of fuel was being worked out and tested in the GDL. The chemical ignition and self-ignition of fuel, an idea proposed by the scientists of the GDL, were also tested.

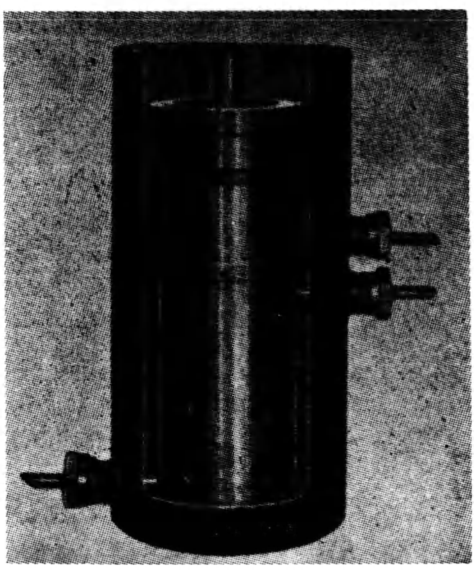
In 1934–1938, while working in the system of the Scientific Rocket Research Institute, the workers who had worked earlier in the GDL created a

family of highly efficient engines from ORM–53 to ORM–102. Some of these engines passed not only static but also flight tests.

Some data on one of the best engines of that time—the ORM–65—can be given as an example. The official static tests of this engine were carried out in 1936. It worked on nitric acid and kerosene. Its thrust could be regulated in the range from 50 to 175 kg. In the nominal regime of ground operation the thrust was 155 kg, engine efficiency being high. In the nominal regime with combustion pressure in the chamber of 22 atm it used 0.738 kg fuel per second. Consequently it had a specific impulse of 210 seconds.

The fuel was delivered to the combustion chamber from balloons. The delivery pressure reached 35 atm in the maximum regime. The combustion chamber and nozzle were cooled externally by nitric acid. The combustion chamber head was cooled from the inside by the components of the fuel entering the chamber.

The fuel components were sprayed into the combustion chamber through centrifugal injectors (three injectors or oxidizers and three injectors for the fuel). The ignition device consisted of a pantograph spark plug, cartridges with electro-primer and a pyrotechnical igniter.



The first Soviet liquid-propellant rocket engine ORM–1.

The ORM–65 engine weighed only 14.26 kg and was 465 mm long. The diameter of the chamber was 175 mm. The maximum diameter of the engine taking into account the tubing attached to the chamber equalled 345 mm. The combustion chamber had a volume of 2.015 liters.

The ORM–65 engines withstood short-duration flights. For instance, ORM–65 No. 1 worked for 30.7 min in 49 launchings including 20 static tests (from September 17 to November 5, 1936), eight launchings on aerial torpedos (April 20, 1937 to October 8, 1938) and 21 launchings on the rocket glider RP-318-1 during ground tests (from December 16, 1937 to January 11, 1938).

The engine ORM–65 No. 2 at its sixth launching on March 11, 1938, during ground testing on a rocket glider worked continuously for 230 seconds. During the fourteenth test on January 29, 1939, it worked on an

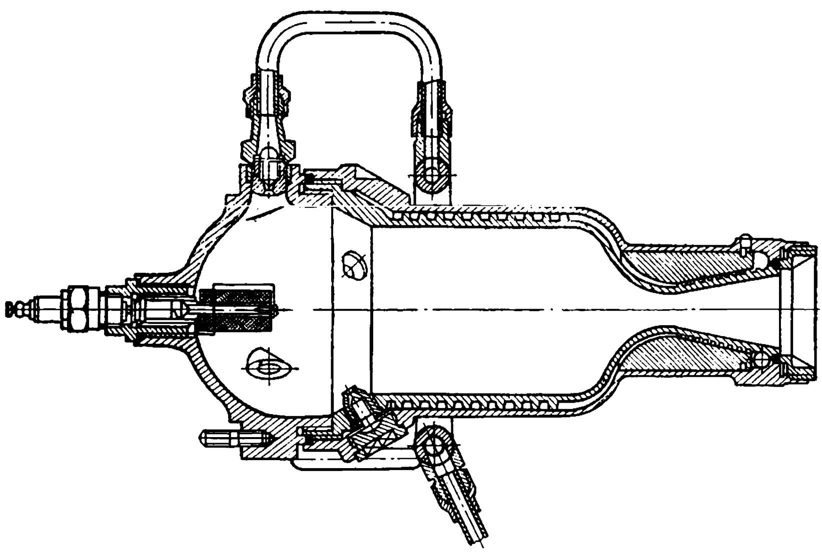
aerial torpedo in flight.

The flight tests of aerial torpedos with the engine ORM–65 were repeated on March 8, 1939. During flight tests the rocket engine, as was established by observation, functioned normally.

The technical data of the engine ORM–65 give a clear idea of the level of development of Soviet rocket engineering in those years.

The collective of the GIRD began work on liquid-propellant rocket engines with construction and testing of the engine OR–2. Its construction was completed in December, 1932. Its hot tests began on March 18, 1933.

The engine OR–2 underwent its first tests in the same form as when it was designed by F.A. Tsander. Later the workers of the GIRD brought about many changes in its construction. New forms of the engine in accordance with the unit system accepted by the GIRD were specified by index 02. After the first tests it was decided to replace kerosene with ethyl alcohol. In the new variants of the engine 02 the steel walls of the combustion chamber and nozzle were covered on the inside with a fire-resistant material and heat insulation. Externally the chamber and nozzle were cooled by liquid oxygen. The oxygen, which was heated during this process, gasified and entered the combustion chamber through holes in the walls. The combustible was meanwhile sprayed in by the jet injectors.



Liquid-propellant rocket engine ORM–65.

During testing of the engine 02 the graphite lining of the chamber was tested. With this chamber lining the engines worked up to 60 seconds. In the final variant of the engine, however, the chamber lining was made of

corundum and that for the nozzle of magnesium oxide. During final tests the engine worked successfully, developing thrust up to 100 kg. The pressure in the combustion chamber was 11 atm.

The engine 02 was intended for the rocket-glider GIRD-RP–1 and so it was designed for prolonged operation (up to 5 min) and repeated launchings. When the first group of jet propulsion studies set out to design the rocket it was decided to create for it some other engine which would satisfy somewhat different requirements. For instance, the operational time for such an engine was supposed to be only 20 sec and in flight it was supposed to operate only once. The new engine was identified by the index 10. Initially it was decided to use a metallic propellant in this engine. But after a number of unsuccessful experiments it was decided to switch to a propellant consisting of benzine and liquid oxygen. In this engine the combustion chamber was pear-shaped. The walls of the chamber and the nozzle which were made of stainless steel were cooled by liquid oxygen. The engine had a small pre-combustion chamber where the benzine and oxygen were injected through (jet) injectors. In the pre-combustion chamber the propellant was mixed and injected into the main chamber, where it was ignited by an electric spark plug.

Reminiscing about the work on creation of this engine, E.K. Moshkin, engineer and one of the workers of the first group of jet propulsion studies, recalls: "During initial test firings many defects in the construction of the engine were revealed. It was found, for instance, that under the action of the large difference of temperatures between the products of combustion and the liquid oxygen thermal stresses arose, leading to the destruction of the chamber. In the beginning there appeared a crack and later the gases leaking from the chamber made the metal melt...

"After the experimental data had been worked out it was decided to replace kerosene with ethyl alcohol as in the case of the 02. At the same time the pear-shaped pre-combustion chamber was replaced by a cylindrical one. Test firings showed that the cooling of the walls was inadequate. With further work by the GIRD workers it was possible to provide reliable, stable operation of the chamber and a steady cooling regime. Since the duration of reliable operation of the chamber satisfied the requirements it was decided to mount the engine on the rocket GIRD-X."

Continuing work on the construction of liquid-propellant rockets, the GIRD group created a number of successfully functioning constructions. These included engines for all the GIRD rockets and a number of experimental rocket engines, which were designed and produced for use on various flight vehicles. For instance, in 1935 the engine 12-K, which developed a thrust of 300 kg after perfection, was designed and fabricated. It worked on 96 per cent ethyl alcohol and liquid oxygen. The pressure of the gas in the combustion chamber reached 14.5 atm.

In 1938–1939 the engine M–29 was designed and produced. It too worked on alcohol and liquid oxygen. With a chamber pressure of 18 atm it developed 200 kg thrust. This engine had a castable refractory and cooling by circulating liquid oxygen.

In the first 10 years of the development of Soviet rocket engine construction, i.e. from 1931 to 1941, more than 100 different designs of liquid-propellant rocket engines were prepared, tested and produced in the USSR.

The success achieved in the construction of rocket engines made it possible, even in the first half of the thirties, to launch a number of Soviet rockets of different designs.

The first rockets

The foundation of Soviet rockets was laid in the GIRD under the guidance of S.P. Korolev. There were four teams in the GIRD. The first team, dealing with the creation of rocket engines and rockets, was headed by F.A. Tsander, the second, dealing with rockets, by M.K. Tikhonravov and the third, concerned with research on air-breathing jet engines, by Y.A. Pobedonostsev. The fourth team, dealing with the winged rockets, was led initially by S.P. Korolev and later by E.S. Schetnikov.

In 1933 four types of rockets were designed and constructed in the GIRD. They were designated by the indices 05, 07, 09 and 10. At the same time a winged rocket with a rocket engine, GIRD–06, was produced by the fourth team.

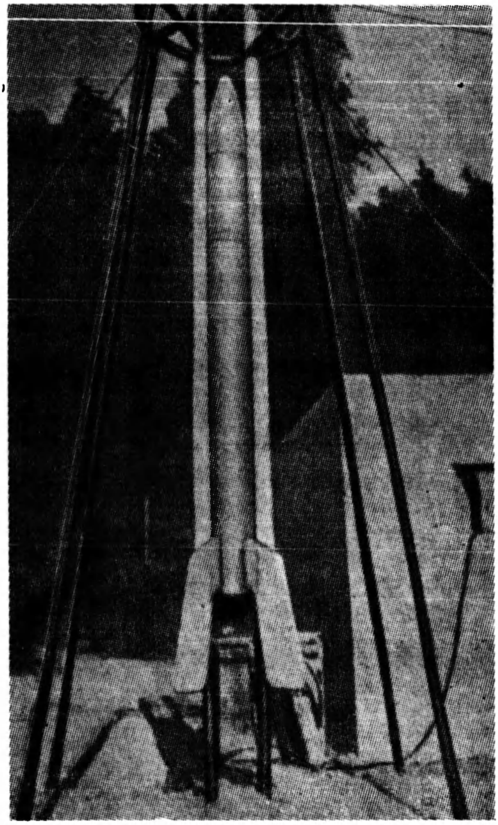
The first Soviet rocket to take off into the sky of our motherland was one of Tikhonravov's design, GIRD–09. It was 2.5 meters long with a diameter of 180 mm. Its launch weight was 19 kg including 8.2 kg of construction, the weight of the propellant being 4.8 kg and payload (instruments and parachute) 6.2 kg.

The engine of the rocket 09 developed a thrust of 52.4 kg and operated for 15–18 secs. Liquid oxygen and "solid" benzine (solution of rosin in benzine) were used as the propellant. Static tests of the engine of the rocket 09 began on April 17, 1933. At first the engine worked for 25 seconds. The tests and perfecting of the engine were completed at the beginning of August, after which the decision to mount it on the rocket was taken. Simultaneously with the engine tests the components of the rocket, including the launching system, were worked out.

On August 17, 1933, the successful launching of the rocket GIRD–09 took place. This was the first Soviet liquid-propellant rocket. On this day Soviet rocket construction was born. On the next day a wall paper was released in the GIRD with the headline "Soviet rockets will conquer space." The words of the GIRDites proved to be prophetic.

During the first launchings the rocket 09 climbed to an altitude of 400 m.

In subsequent launchings it reached 1,500 m. In 1933–1934 alone six successful launchings of rockets of this type took place.



The first liquid-propellant rocket of M.K. Tikhonravov's design on the launching pad.

The second Soviet rocket was the rocket GIRD–X. Its length was 2.2 m, diameter 140 mm, launch weight 29.5 kg, weight of the propellant 8.3 kg, payload 2 kg. The engine worked on liquid oxygen and alcohol and developed a thrust of 70 kg. The operational duration of the rocket engine was 22 sec. The rocket had the shape of a cigar with a sharp nose. In the tail portion of the rocket four Duralumin oblong stabilizers were mounted reaching almost halfway up the rocket body.

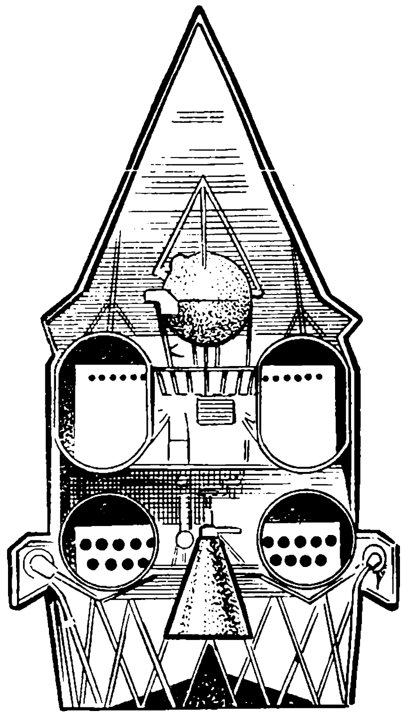
The rocket consisted of five sections. The front section contained a parachute with a jettisoning device. In the second the oxygen tank was situated. The next one accommodated a two-liter balloon with compressed air (105 atm). Here the rocket's main launching accessories were located (safety valve, air valve, manometer, oxygen return valve and oxygen valve). The last section but one was the alcohol tank. Through it passed the liquid

oxygen pipe. The last (lowermost) section was for the engine and the pipe supplying the propellant components to the combustion chamber.

The rocket GIRD–10 was launched on November 25, 1933.

The first rockets of the GIRD signaled the beginning of wide-scale activity in the design and flight testing of liquid propellant rockets in the USSR.

The tests of the first Soviet rockets provided ample scientific data. They made it possible to check the working capability of all the elements of rocket construction in practice, primarily those of the engines. The results of the tests helped to define the direction of further investigations and constructional work. The teams of the GIRD, the Scientific Rocket Research Institute Number one and other organizations learned from the experience obtained during the testing of the first rockets. This experience laid the foundation of the further development of Soviet rocketry.



Plan of the third stage space rocket with Luna–1.

The significance of the successful flights of the first rockets of the GIRD very much outweighs the limits of the scientific material obtained thereby. The launching of rockets has immense significance for the confirmation of the realities of work in the field of rocket engineering. They showed that our science, engineering and industry had achieved the necessary level for this and that the teams of Soviet rocket constructors formed under the guidance of the GIRD were capable of solving the most complicated problems in constructing flight vehicles of the new type.

The first rockets produced a "chain reaction" in designing, constructing and testing of liquid-propellant rockets. In order to show how widely these activities were spread across the USSR in the 30s we will give some more examples of rockets built in those years without detailing their technical specifications.

First of all we will mention here that the GIRDites (while working with the RNII) had tested the rockets GIRD–07 and GIRD–05 in flight (the latter had a launch weight of 97 kg and an alcohol-oxygen rocket engine

with a thrust of 300 kg).

In 1934 tests on a liquid-propellant winged rocket—the GIRD–06—of S.P. Korolev's design were carried out. On the basis of the results of these tests a winged rocket, the "212", with the liquid-propellant rocket motor ORM–65 was designed in the Scientific Rocket Research Institute Number One. The rocket had hydraulic stabilization and an automatic control system.

During the transition of the GIRD to an industrial set-up S.P. Korolev saw to it that the extensive work of a scientific-technical nature of the jet propulsion section, attracting a large body of people to creative work in this field, was not stopped. On his initiative a jet propulsion section was organized in TsS Osoaviakhim at the base of a large social group formed by the GIRD. This worked from 1934 to 1938, initially in the capacity of a military-scientific committee and later as the stratosphere committee headed by one of the veterans of Soviet aviation, P.S. Dubenskii. I.A. Merkulov was elected leader of the jet propulsion section.

The jet propulsion section of the stratosphere committee worked on the scientific propagation of rocket engineering and publication of scientific literature, training of engineering-technical personnel and design of rockets. This section numbered the enthusiasts of rocket engineering who carried on work on the society level, combining it with production or teaching in institutes. Those taking an active part in the working of the jet propulsion section of TsS Osoaviakhim* were outstanding specialists of rocket engineering. In the forefront were the leaders of the GIRD and the engineers of GDL: S.P. Korolev, M.K. Tikhonravov, V.P. Glushko, Y.A. Pobedonostsev, A.I. Polyarnii, V.I. Dudakov, G.E. Langemak and together with them Professors V.P. Vetchinkin, B.S. Stechkin, K.A. Putilov, A.V. Kvasnikov, K.L. Baev, B.M. Zemskii, F.I. Frankel'. The training of engineering personnel specializing in rocket engineering was guided by the designer of the first indigenous rocket engine, V.P. Glushko. M.K. Tikhonravov headed the editing of the journal *Jet Propulsion.*

In 1936 the jet propulsion section carried out the construction of a liquid-propelled rocket designed under the guidance of A.I. Polyarnii. The rocket engine worked on alcohol and liquid oxygen, developing a thrust of 40 kg. The first test launching of this rocket took place in 1936.

In 1937 the jet propulsion section of the strastosphere committee constructed a rocket designed by A.F. Nistratov and I.A. Merkulov. The engine worked on alcohol and oxygen. Besides this water was sprayed into the chamber, which somewhat lowered the specific thrust but simplified the chamber cooling.

*TsS Osoaviakhim—Central Council of the Society for Assistance to Defense, Aviation and Chemical Construction of the USSR—General Editor.

Interesting activities in the construction of rockets were also pursued in Leningrad, first of all at the GDL, whose collective built and statically tested in 1933 ther ocket with the engine that worked on kerosene and nitric acid, and developed a thrust of 200 kg.

In 1935 in the Leningrad GIRD a rocket of original construction was built according to the design of V.V. Razumov. The engine consisted of two combustion chambers which rotated about a longitudinal axis. The rotation of the chambers generated centrifugal force which drove the propellant into the chamber.

In 1936 the group of GIRDians organized one more bureau of rocket construction. A.I. Polyarnii and E.P. Sheptitskii worked in it as the guiding specialists.

In 1937 the collective of this bureau carried out flight tests on a rocket with a launch weight of 30 kg. An alcohol-oxygen engine with a thrust of 100 kg was installed. In three years this collective carried out a number of launches of rockets, many of which reached an altitude of 5,000 m.

It was this collective that designed and built the rocket with a hybrid motor that worked initially on a solid propellant and later on a liquid propellant consisting of alcohol and liquid oxygen. The weight of the rocket was 10.5 kg. The first series of tests of these rockets was in 1938, at which time the engine worked only on solid propellant. During the tests the rockets climbed to an altitude of 2,000 m.

In writing about the wide front of work in the field of Soviet rocketry it is necessary to note one more highly interesting part of this work. In 1932, in the early days of the GIRD, research on air-breathing engines was started. After exhaustive experimental investigations of static models Y.A. Pobedonostsev designed a missile in which was installed an air-breathing jet engine. In GIRD this apparatus went under the index "08". In 1933–1934 three series of flight tests of missiles with air-breathing jet engines were carried out. The initial velocity of the missile was obtained in a gun barrel. The engine was switched on in free flight. Thanks to the operation of the jet engine the flight range was considerably increased. These flight tests of air-breathing jet engines were the first of their kind in the world. The missiles designed by Y.A. Pobedonostsev were the first jet apparatuses to enter the realm of supersonic velocities.

In 1936, on the basis of the experience of experimental research on air-breathing jet engines in the GIRD, I.A. Merkulov designed a rocket with an air-breathing jet engine. Sixteen such rockets were built and tested in the year 1939. They were two-stage rockets, the first stage of which was a solid-propellant rocket, while the second stage had an air-breathing jet engine.

The launching weight of the rocket was 7.07 kg: the first stage weighed 3.51 kg and the second 3.56 kg. The first successful flight test of this rocket was carried out on March 5, 1939. The official tests took place on May 19,

1939, with accurate measurements of flight altitude. At the time of this launching the rocket climbed to an altitude of 625 m under the power of the first-stage engine where, at a velocity of 105 m/sec, the second-stage engine was switched on. The first, solid-propellant, stage detached itself from the second stage with the help of aerodynamic brakes, and fell to earth while the second stage, impelled by the air-breathing jet engine, attained a velocity of 224 m/sec and climbed to an altitude of 1,800 m. This was the first rocket in the world with an air-breathing jet engine.

In 1940–1941 Soviet constructors carried out flight tests of a series of rockets of fairly large size. The new rockets had a launch weight of 180–187 kg. The propellant stored aboard weighed 59 kg. The weight of the payload reached 25 to 30 kg. The length of the rocket was 3.12 m and the diameter was 203 mm. The rockets had hybrid engines which worked for 0.86 sec on solid propellant with a thrust of 3,840 kg and later for 10 sec on the liquid propellant, whose components were kerosene and nitric acid. During flight tests the rockets were launched inclined to the horizon and they traveled a distance up to 20 km.

We have listed here a number of rockets built in the USSR in the prewar period, named their constructors and mentioned the organizations that built them so as to show, by the example of rocket building in the thirties, that Soviet rocket engineering was created by the whole nation, that our rockets are the result of the work not of individual scientists or inventors, but of the children of the nation raised on the creative labor of the Great October Revolution.

After initial testings, activity in the field of rocket engineering concentrated on investigating the engines, on learning the combustion processes of the liquid-propellants, on launching of rockets and cooling of combustion chambers, on creating the propellant feed system and the engine control system.

A number of projects were devoted to the dynamics of rockets, the solution of the problem of stability in flight and of the construction of apparatus to control them.

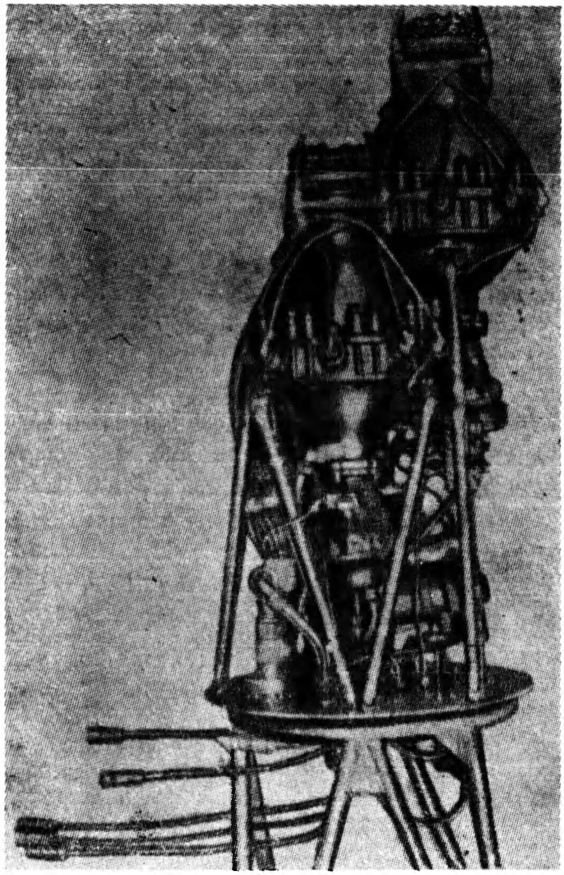
In the following years activity in the field of rocket engineering did not, as a rule, cross the boundaries of the laboratories, experimental construction bureaus and testing grounds. Much experimental material was accumulated over these years.

As a result of successful work on liquid-propellant rocket engines many highly effective units were created. In 1943 the engine RD–1, with a thrust of 300 kg, was built and underwent official static and flight tests.

During the years 1943–1946 nearly 400 tests firings were carried out on aircraft on different designs fitted with the engines RD–1 and RD–3: the "Pe–2" of Petlyakov, the "La–7R" and "120–R" of Lavochkin, the "Yak–3" of Yakovlev, the "Su–6" and "Su–7" of Sukhoi.

The engine RD–2, which also underwent static tests, had a thrust of 600 kg (1946). An experimental three-chamber engine with gas-generator and turbo-pump aggregates with 900 kg thrust underwent static tests in the years 1944–1945.

With the development of rocket engineering new groups of designers joined in rocket engine construction.



Liquid-propelled rocket RD–3.

Explorers of high altitudes

On the basis of the experience obtained by Soviet rocket production over many years high-altitude rockets for scientific purposes were built. In the mid-forties the practical application of rockets for scientific investigations began in the USSR. High-altitude rockets with automatic equipment began to be used for a wide complex of geophysical, astrophysical and bio-medical research.

Starting from 1946, the launching of rockets with scientific equipment became one of the basic means used by Soviet scientists to probe the upper atmosphere. The first rocket to climb an altitude of 110 km was launched in May, 1949.

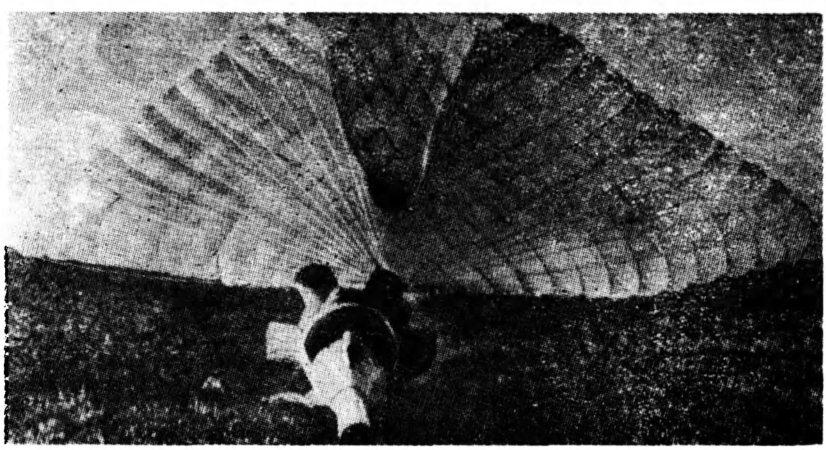
On the basis of the results of this experiment it became possible to formulate the distinct requirements relating to a given line of research and the equipment needed. After this special rockets were constructed to the specifications of the Academy of Sciences of the USSR. Later, on the instructions of the central aerological observatory, so-called "meteorological" rockets were designed and built. Starting from 1951 these rockets were used for systematic investigation of the atmosphere. With the experience accumulated the design of rockets and the instruments mounted on them was perfected.

Let us learn about the construction of one of the Soviet meteorological rockets. It consists of a 5 m long body and a 2 m long nose section. In the rocket body there are tanks with fuel and oxidizer, and a balloon with compressed air to feed the fuel to the rocket engine. The tail-fins for stabilization of the rocket flight are fixed on the outside to the lower part of the body. The weight of the body is 220 kg.

In the nose section of the rocket are accommodated measuring equipment, a parachute for descent and a powder (rocket) engine for the separation of the nose section of the rocket from the body.

At the time of launching the powder (rocket) engine operates. It accelerates the rocket to a velocity of 170 m/sec.

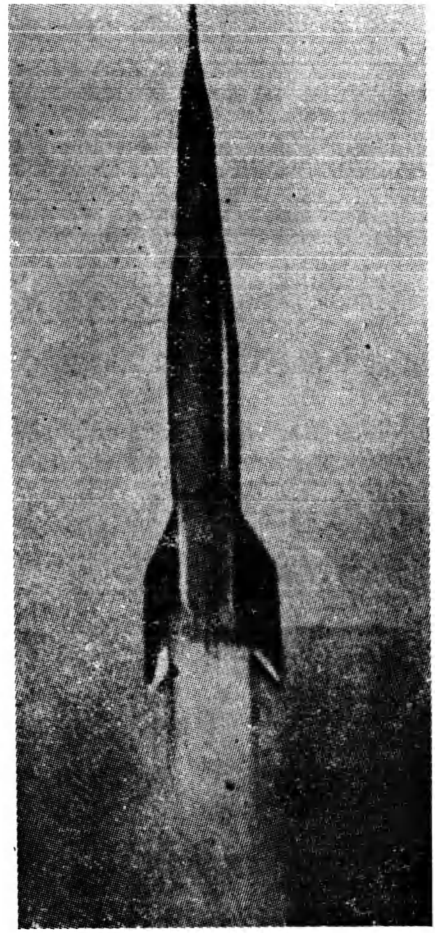
After the whole powder charge burns out the starter rocket is separated



The use of rockets for exploring the upper layers of the atmosphere began in our country in 1947. The nose section of a geophysical rocket with measuring instruments while landing by parachute.

and the second stage continues to climb under the action of the rocket engine reaching a velocity of more than 1,100 m/sec at an altitude of 30 km. At this time the propellant tanks dry up but the rocket continues to climb due to inertia.

At an altitude of nearly 70 km the nose section is separated from the body. After reaching the maximum altitude the nose section of the rocket begins to fall. The opened parachute reduces the velocity of descent and the rocket lands with a velocity of 4-5 m/sec. At such a landing speed nose section of the rocket and all the measuring equipment located in it are preserved for use on subsequent flights. Only the sources of power supply and the dowel pin with which the rocket crashes into the ground on landing are replaced. The body of the rocket is also set down by parachute and after overhaul and repairs the stabilizers are used for subsequent flights.



In 1957–1958 geophysical rockets with scientific equipment weighing 1.5 tons reached an altitude of 500 km. Launching of a geophysical rocket.

The collectives of different scientific and research institutes took part in the study of the atmosphere. The overall coordination of the project was accomplished by the Academy of Sciences, USSR.

The use of rockets for investigating the upper layers of the atmosphere made available abundant scientific material on the structure of the stratosphere and the ionosphere, cosmic radiation and the influence of high-altitude conditions on living organisms.

During the International Geophysical Year Soviet scientists launched hundreds of rockets for study of the atmosphere. They took off from the arctic and medium-latitude zones of the USSR, from ships on long voyages and from the Antarctic.

In 1957 still more powerful geophysical rockets were built. From 1958 single-stage geophysical rockets with a payload of more than 1.5 tons of scientific equipment climbed to an altitude of nearly 500 km.

COSMIC SPEEDS

In launching earth satellites, in the flight of rockets to the moon and in putting automatic stations into orbit as solar satellites attention was always primarily directed to the attainment of cosmic speeds.

Why speed ?

The amazing flights of Gagarin, Titov and other Soviet cosmonauts in elliptical orbit around the earth would not have been achieved without the spaceships *Vostok*, *Voskhod* and *Soyuz* achieving the necessary speed. Why? In what respect do cosmic flights differ from terrestrial travels by any mode of transport?

The essence of this difference is the following: In order to realize cosmic flight an enormous amount of energy is required. It is necessary to perform work amounting to more than 6,000,000 kg·m for every kilogram weight of a spaceship on earth in order to overcome the earth's gravitational force and fly into the cosmos. The last stage of the first Soviet space rocket weighed 1,472 kg. Consequently the energy transmitted to it equalled 10,000,000,000 kg·m. The source of energy for the engines which accelerate the rocket is the propellant. Its quantity exceeds by many times the weight of the load to be carried to the cosmos. If rocket engines are to work throughout the flight, like the engines of automobiles or aircraft, then there must be sufficient propellant aboard the rocket to keep the engine working. This means that it is necessary to lift not only the spaceship itself but also an enormous store of propellant.

To accomplish interplanetary flights so much propellant is needed that it is impossible to lift it to cosmos. Is it not possible to use some other form of energy, not the chemical energy of fuel, where no propellant is necessary ? Such energy exists. It is kinetic energy. It, so to speak, weighs nothing. However large the amount of kinetic energy transmitted to the rocket not a single gram of propellant need be spent to transport it. That is why at the time of take-off the necessary amount of kinetic energy has to be given to the interplanetary spaceship, i.e. to accelerate it to the required velocity so that it can then fly millions and hundreds of millions of kilometers in outer space without spending any propellant on its movement.

In recent years many works have been published on electrical rocket engines which could be used on interplanetary spaceships flying between the orbits of earth satellites and those of other planets. These engines produce a very small thrust but operate for a long time. In this book we

are not going to consider the peculiarities of flights with such engines.

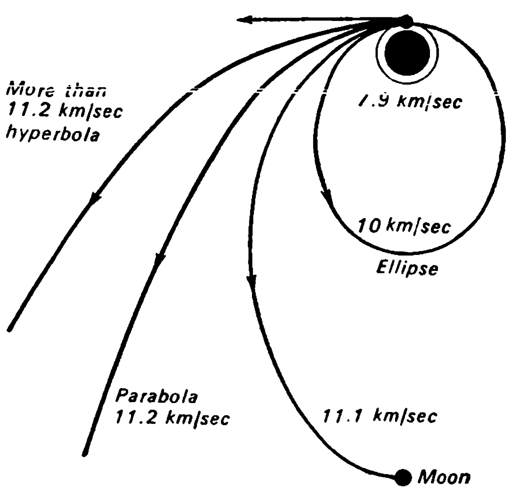
Take off

The path of a ship in space, i.e. the orbit along which it moves around the earth or on its interplanetary course, is basically determined in those minutes during which the altitude and flight speed are gained under the action of the rocket engine. Thereafter orbital flight can last for many days and, in the future, years with the engine stopped and, as is expected to be done in the majority of cases, with the spaceship separated from the launcher rocket. On the ship itself after its separation from the rocket there remain only small engines for stabilizing the spaceship's attitude in space and correcting the trajectory and of course the engine unit that ensures the landing of the spaceship on the planet and its return to earth.

It is the usual practice to divide a rocket flight into two phases having an essential qualitative difference one from the other. The first is the phase of active flight when the rocket moves with the engine operating. It is during that phase of the flight that the rocket accelerates to the specified velocity. Therefore it can also be called the boost phase of the rocket. In the second phase of the flight, called the passive phase, the rocket flies with the engine shut off, under the influence only of the gravitational forces of the earth, moon, planets and sun.

A space apparatus needs a particular speed to carry out a set flight.

Let us first consider the speeds that a rocket must develop at take-off



The path of the rocket is determined by its speed. At a speed of 7.9 km/sec the rocket becomes earth's satellite. At a speed of 11.1 km/sec it reaches moon. At a speed of 11.2 km/sec it overcomes earth's gravity and is separated from it forever.

from the earth. Here, as is known, three cosmic speeds are of fundamental importance. We will define precisely the physical nature of these speeds.

Orbital velocity is the velocity that a space apparatus lifted by a rocket into outer space must possess in order to become the artificial satellite of the planet and move around it in circular orbit. This velocity is also called the "circular" velocity.

The physical meaning of orbital velocity is that at this velocity of flight the centrifugal force is exactly equal in magnitude to the gravitational force of the earth.

From the condition of equality of magnitudes of the centrifugal force and weight:

$$\frac{MV^2}{R} = Mg$$

it is easy to obtain the magnitude of orbital, or circular velocity. It is equal to

$$V_k = \sqrt{gR}.$$

On the surface of the earth at the equator $g = g_0 = 9.814$ m/sec² and $R = R_0 = 6{,}378{,}250$ m. Therefore

$$V_{k0} = \sqrt{g_0 R_0} = 7{,}912 \text{ m/sec}$$

and if the earth had no atmosphere, like the moon and mercury, it would have been possible to launch a satellite with this velocity at a very small height above the surface of the earth.

Escape velocity is the velocity that a rocket must develop in order to overcome the gravitational force of the earth and fly into outer space.

On acquiring this velocity the rocket moves not along a closed orbit around the earth but along a parabolic trajectory, separating forever from our planet. This velocity, therefore, is often called "parabolic."

In order to tear loose from the bonds of gravity a rocket must have kinetic energy equal to the work it is supposed to perform. According to the laws of mechanics the amount of work necessary to take a certain body beyond the limits of the earth's gravitation is equal to that which would have been necessary to lift this body under constant magnitude of gravitational force to the height of one radius of the earth. From the condition that the kinetic energy stored by the rocket must be equal to this work is determined the magnitude of the escape velocity, i.e. on the basis of the equality $MV^2/2 = MgR$ the required velocity is obtained

$$V_p = \sqrt{2gR}.$$

For the surface of the earth on the equator $V_{p0} = 11{,}189$ m/sec.

The magnitude of the parabolic velocity is $\sqrt{2}$ times, i.e. about 40%

more than the circular one. This correlation of velocities is true not only for the earth but also for other planets and stars.

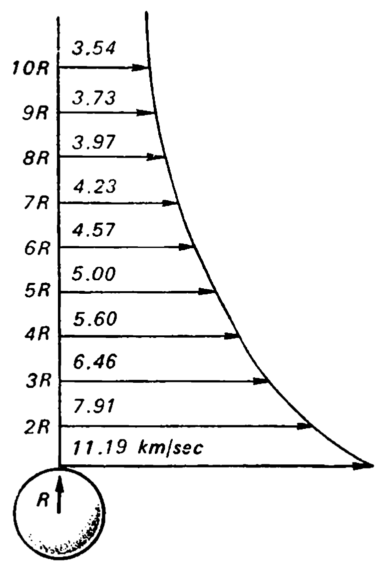
Solar escape velocity is the velocity that a rocket must develop in order to overcome solar gravitation and fly toward other stellar worlds.

Having developed parabolic velocity the rocket moves away from the planet into outer space. But here it comes under the influence of solar gravitation and begins to move around it, transforming itself into a new planet of the solar system. For the space apparatus to cross the boundaries of the solar system and reach the orbits of other planets it must still have some stock of energy. This additional energy is needed in order to perform the work of overcoming the solar gravitational force. The amount of energy required for a rocket being launched from the earth to reach other planets can be characterized by the magnitude of the flight speed. The larger the speed of the rocket, the farther it can fly from the sun, reaching more and more distant planets. At a velocity of 16.7 km/sec a rocket can break the bonds of solar gravitation and leave our planetary system forever. This velocity is also called the "third cosmic" velocity.

Although at this velocity a rocket begins to move away from the earth along an arc of a hyperbola the third velocity is not called "hyperbolic" since all velocities larger than parabolic are hypersonic.

Altitude and velocity

In popular science literature on astronautics the magnitudes of the cosmic velocities for a rocket flight near the surface of the earth are usually given. We did the same thing at the outset. But we must add here that the magnitude of velocities can be considered only as abstract or conditional velocities. They would have been of actual importance only if our planet had no atmosphere and if it were possible to think of a flight with cosmic velocity in the vicinity of the earth's surface. It is from an altitude of 150–200 km up that the air becomes so rarefied that it offers only negligible resistance to the vaulting flight of the orbital spaceship. At an altitude of 200 km the density of the air is nearly one billion times less than that at the surface of the earth.



Magnitude of escape velocity at various distances from the center of the earth.

It is necessary to note here the following interesting phenomenon: We said just now that during the motion of a satellite within atmospheric limits it faces air resistance due to which the velocity of its flight decreases. All this seems to be quite clear: air retards the motion of the satellite and its velocity decreases. It is difficult to imagine the reverse picture where the velocity of the satellite is increased due to acceleration by air. But this is exactly what happens in reality. Let us consider this question more carefully. Air, of course, retards the flight of a satellite. And if the satellite were flying at a constant altitude its velocity would be considerably decreased under the influence of air resistance. But even with the minutest loss of velocity the satellite comes down to a lower altitude. During this its potential energy is converted into kinetic energy and the flight velocity increases. Thus, as a result, due to air resistance a reduction in the satellite's flight altitude produces an increase in its velocity.

At an altitude of 200 km a rocket can attain not only circular but also large hypersonic velocities. Many scientists, therefore, quote the values of various cosmic velocities for the altitude of 200 km above the earth's surface.

How do the magnitudes of cosmic velocities vary? Do they increase or decrease with the climb?

According to the law of gravitation, the force with which all bodies are attracted toward each other is proportional to the product of their masses and inversely proportional to the square of the distance between their mass centers. Consequently, on lifting any body to a certain height the force with which it is attracted toward the earth, i.e. its weight, continuously decreases.

Therefore after climbing to a certain altitude the rocket needs a smaller velocity in order to become a satellite of the earth, or to fly off into space. For instance, for the altitudes at which the orbits of the *Vostok* spaceships traveled we have the following data: at an altitude of 180 km the circular velocity equaled 7,803 m/sec, at the altitude of 200 km 7,791 m/sec, at 250 km 7,761 m/sec and at 300 km 7,732 m/sec.

The higher the orbital spaceship, the smaller the magnitude of the velocity necessary for it to move along a circular orbit.

The magnitude of the velocity for an artificial satellite moving at a distance of 35,809 km from the earth along the so-called fixed (one-day) orbit equals only 3,076 m/sec. By moving at such a speed it performs a complete circle around the earth exactly in one sidereal day, i.e. in 23 hrs 56 min 4 sec.

The angular velocity of motion of such orbital spaceships is exactly equal to that of the earth's rotation about its axis. If launched in the plane of the equator and placed in motion eastward it would seem to an observer on the earth to be hanging fixed in the sky.

The magnitudes of escape and solar escape velocities are also reduced with (increasing) altitude in similar fashion.

The magnitudes of orbital and escape velocities for different altitudes above the earth's surface are determined by the formulas:

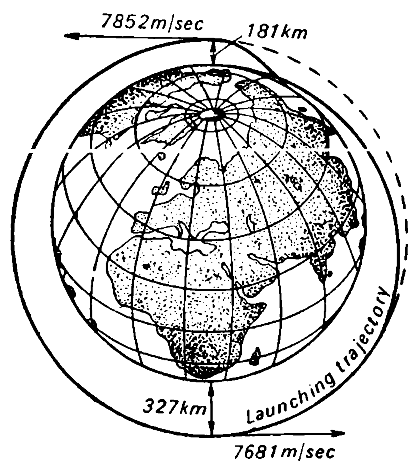
$$V_k = \sqrt{g_0 \frac{R_0^2}{R_0 + H}};$$

$$V_p = \sqrt{2g_0 \frac{R_0^2}{R_0 + H}}.$$

Velocity of a spaceship following elliptical orbit

If the velocity of a satellite differs from the orbital one it will move not along a circle but along an elliptical trajectory.

Here, when the velocity becomes less than the orbital one the spaceship is brought down and descends to the minimum altitude at opposite points of its orbit. The point on the orbit located at the minimum altitude, or more precisely, at the minimum distance from the center of the earth, is called the "perigee." After crossing the perigee the spaceship begins to gain altitude, again returning to the initial level. If, when at perigee, the ship enters the dense layers of air its motion is either steeply retarded or stopped altogether. For instance, if a rocket after lifting a spaceship to 180 km gives it a velocity only 0.5% less than the orbital one, the ship will enter the dense layers of the atmosphere without making a single loop and end its flight.

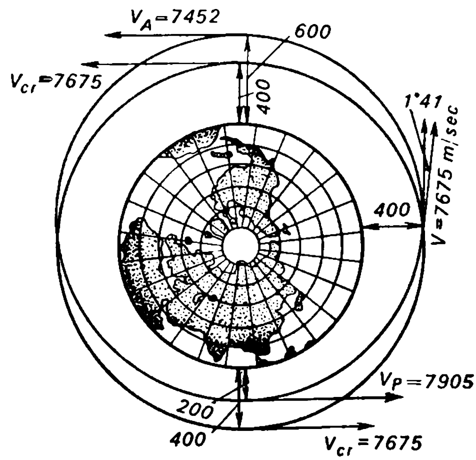


Orbit of the spaceship *Vostok.*

If, on the other hand, the rocket gives the spaceship a velocity which is more than the orbital velocity it will start moving away from the earth along an elliptical orbit. The ship climbs during the first half of the total revolution. After having done this half-revolution the ship reaches its highest altitude. The point on the orbit situated at the maximum distance from the center of the earth is called the "apogee." During the climb the satellite loses a part of its kinetic energy. Therefore after reaching the apogee it is again brought down to its initial altitude.

When movement around the sun is considered the terms "perihelion" and "aphelion" are used. Perihelion is the point of the elliptical orbit

situated at the minimum distance from the sun; aphelion is the point at the maximum distance from the sun. For the central gravitational field, in general, the above-mentioned points must be termed "pericenter" and "apocenter." And all quantities referring to these points: velocity, radius vector and others—are usually expressed with the indices "P" for the pericenter and "A" for the apocenter.



Effect of variation of the direction of flight on the shape of the orbit. A variation in the flight direction of 1°41′ changes a circular orbit at 400 km altitude to an elliptical one with an altitude of 600 km at apogee and 200 km at perigee.

To determine the velocity of a spaceship at any point on the orbit it is necessary to know the magnitude of the major axis of the elliptical orbit along which it moves.

In reporting the launchings of satellites what is usually indicated is not the major semi-axes of the orbits but their altitudes over the surface of the earth. By knowing the radius of the earth R_0 at known altitudes of the orbit at perigee H_P and apogee H_A it is easy to calculate the major semi-axis of the orbit which is equal to

$$a=R_0+\frac{H_P+H_A}{2}.$$

The dependence of the velocity of the spaceship in orbital flight around the earth on the magnitude of the major semi-axis of its orbit and on the distance of the ship from the center of the earth at any given moment while flying at an altitude H can be expressed by a simple formula

$$V_e=\sqrt{gR\left[2-\frac{R}{a}\right]},$$

where $R = R_0 + H$.

The magnitudes of the velocities at the apogee and the perigee of artificial earth satellites following elliptical orbits are related to each other by a simple relation. They are inversely proportional to the orbital radii at apogee and perigee

$$\frac{V_A}{V_P}=\frac{R_0+H_P}{R_0+H_A}.$$

Orbiting period

In the Tass reports on the flights of Soviet spaceships and in news about the launching of earth satellites abroad, the orbital period is always indicated, i.e. the time in which the spaceship performs one complete revolution around our planet.

The orbiting period of a satellite depends on only the quantity—the radius of the orbit along which it moves. If the satellite moves not along a circular orbit but an elliptical one, its orbiting period is determined by the major semi-axis of the ellipse.

The orbital period of an earth satellite can be calculated with the help of an approximate formula

$$\tau^2 = \frac{a^3}{10{,}095}.$$

Change of orbit

An orbital spaceship put into a set path in space by a launcher-rocket moves along it without the help of the engines. Day after day, week after week it untiringly makes revolutions, one after the other, around our planet without spending a single gram of fuel. At an altitude of 300–400 km the satellite spaceship can continue its flight for many months. And during this long period it moves along one and the same, almost fixed orbit. Only the very weak resistance by atmospheric layers gradually reduces the altitude of its flight.

But can an astronaut change the path of his ship at will? Can he accelerate or decelerate its run, lift it to a higher altitude and then lower it again to the previous orbit?

This is an important question of principle. Will the orbital spaceship, like other artificial celestial bodies built by human beings, move like natural celestial bodies along orbits set once and forever or is man capable of creating apparatus obedient to his will which can freely move in space? Science answered this question positively. Man can control the spaceship and change its orbit at will. How is it done? The method, a unique one, is as follows:

Aboard the spaceship, which separates from the launcher rocket, are located rocket engines and the propellant needed for their operation. By switching on these engines the pilot can vary the speed of the ship, which leads to a change in orbit. Consequently, to increase the flight altitude the astronaut must increase the speed of his ship and to decrease it, reduce speed.

If the astronaut increases the flight speed by switching on the engine the spaceship does not move to a higher altitude with a jerk. Having obtained the additional velocity it gains height gradually and reaches its maximum altitude over the earth's surface only at the diametrically

opposite point of the orbit. Any climb of a spaceship that takes place without the help of the operating engines is accompanied by a reduction in the flight speed. At the apogee the speed of the ship turns out to be less than the circular velocity for that altitude. That is why the ship, after passing through the apogee, descends to the initial altitude. Let us consider, for instance, the variation of a ship's flight altitude.

The launcher rocket has put the spaceship into circular orbit at 200 km altitude. The ship began to move along this orbit with a speed of 7,791 m/sec. The pilot has decided to lift the ship to an altitude of 300 km. For this he fires a rocket engine and increases the speed by 29 m/sec. Having gained a velocity of 7,820 m/sec the ship goes along the arc of an ellipse climbing to 300 km at the apogee. Here its speed is reduced to 7,703 m/sec. The circular velocity for the altitude of 300 km, however, is 7,732 m/sec. Since the flight speed has turned out to be less than the circular one the ship begins to descend during the subsequent part of the orbit and returns again to the altitude of 200 km where its speed again reaches 7,820 m/sec. Thus the ship will make revolution after revolution along an elliptical orbit located at altitudes from 200 km to 300 km. It must be noted here that when it flies at a mean altitude of 250 km its speed will be exactly equal to the circular velocity for the given altitude (7,761 m/sec). It will not remain at this altitude but will move along a circular orbit because its speed at this altitude is not horizontal but at a certain angle to the horizontal, which in this case is half a degree. Due to this orientation at this speed the ship will begin to climb 50 km higher.

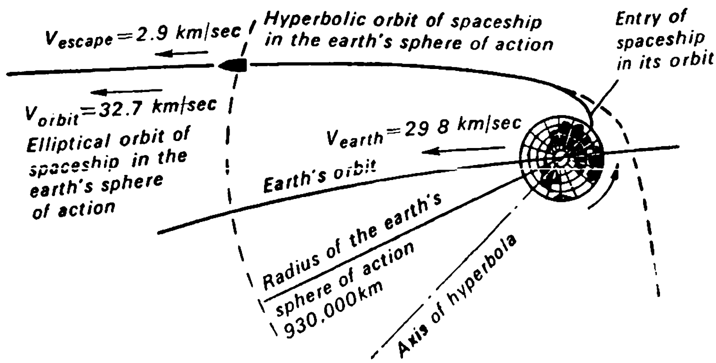
In order that the ship, after climbing, does not descend to the previous altitude but continues to move at an altitude of 300 km along a circular orbit the pilot must maneuver it in the following manner: It is clear that in order to move it along a circular orbit the speed of the ship should be increased by 29 m/sec at the moment when it is situated at the apogee moving perfectly horizontally. Thus with the help of two successive maneuvers it is possible to lift a spaceship from one circular orbit to another lying at a higher altitude without changing the plane of the orbit.

By knowing the laws of motion of an orbital spaceship the astronaut can guide its flight by varying the speed and altitude of the flight in accordance with the assignment. For maneuvering in space the ship must have on board the required stock of propellant. The theory of rocket motion worked out by K.E. Tsiolkovskii allows us to determine the quantity of propellant necessary for the given maneuver, and this subsequently allows us to estimate the mass of the whole powerplant (engine, control members, propellant tanks and propellant storage).

Earth escape velocity

Let us consider one more cosmic speed which is of fundamental impor-

tance in the problem of interplanetary communications. It is the speed with which the spaceship, having overcome the planet's gravitational force, moves away from it to the boundless distances of the universe.



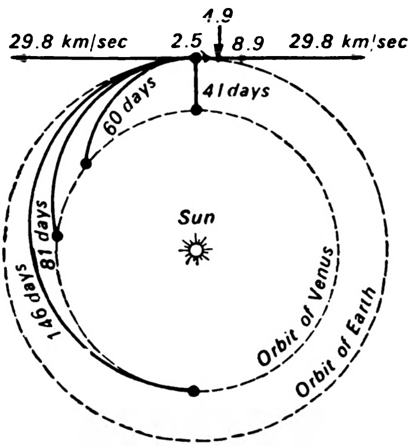
Exit of interplanetary spaceship from the zone of earth's influence during flight to Mars.

Let us imagine that a rocket, after being launched vertically upward, has passed through the dense layers of atmosphere and after attaining escape velocity zooms into outer space. Will its flight speed be constant? Of course not. With the lapse of every second, and with the gain of every kilometer of altitude the speed of the rocket will diminish. When it reaches an altitude of 1,000 km its speed will be reduced to 10,403 m/sec. At an altitude of 10,000 km the speed will be 6,983 m/sec. At 100,000 km above the earth's surface it will be only 2,740 m/sec. Thus the rocket will move farther and farther away from the earth at a continuously decreasing speed. And when it approaches the boundary of the earth's gravitational zone the whole of its kinetic energy will be exhausted.[1] The velocity of the rocket relative to our planet, i.e. earth escape velocity, turns out to be negligibly small, practically equal to zero. Consequently after attaining escape velocity a flight vehicle overcomes the gravitational force and does not fall back onto the earth's surface but at the same time will not move away from its orbit. Along with the earth it would begin to move around the sun in an orbit identical, or almost identical, to the earth's.

Suppose we want to send a spaceship to Mars or Venus, i.e. to make it move away from the earth's orbit. It is evidently necessary to transfer to the spaceship during launching such a quantity of energy that it will not only overcome the gravitational force, but also maintain the necessary velocity beyond the zone of the earth's gravity. To do this the spaceship

[1]The zone of earth's gravity or the zone of the earth's influence is the space where the planet, rather than the sun, must be considered as a central body in calculating the motion of space apparatuses.

must possess a velocity during take-off from the earth considerably higher than escape velocity.



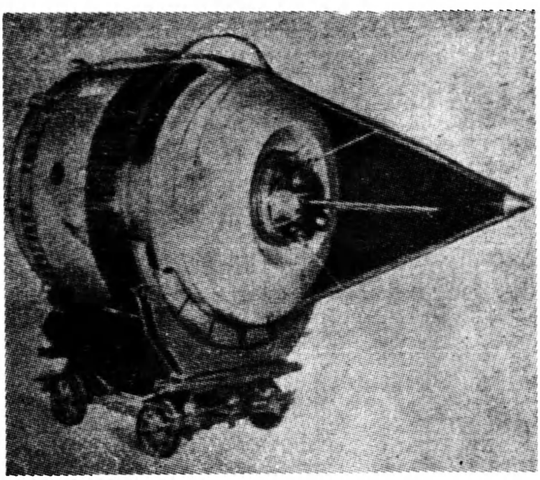
The duration of a flight from the earth to the orbit of another planet depends on the velocity that the interplanetary spaceship attains during exit from the zone of the earth's influence. The greater the velocity the less the duration of a flight to Venus.

The higher the escape velocity needed for the spaceship to escape the earth the larger the velocity the rocket engines must impart during take-off from the cosmodrome. For instance, in order to reach the orbit of Venus the spaceship must move away from the earth with a speed of at least 2,494 m/sec. For this its speed at take-off from the earth must be 11,464 m/sec. To reach the orbit of Mars, the earth escape velocity required is not less than 2,943 m/sec and the launching speed must correspondingly equal 11,570 m/sec.

For the spaceship to move away from the earth with a speed of 10,000 m/sec the launcher rocket must impart speed of 15,007 m/sec at take-off.

The required launching speed of a rocket can be determined by the formula:

$$V=\sqrt{V_P^2+V_S^2}\,.$$



A space rocket was launched toward the moon on January 2, 1959. It placed an automatic station, Luna-1, in space. The last stage of the rocket with half of the nose cone removed.

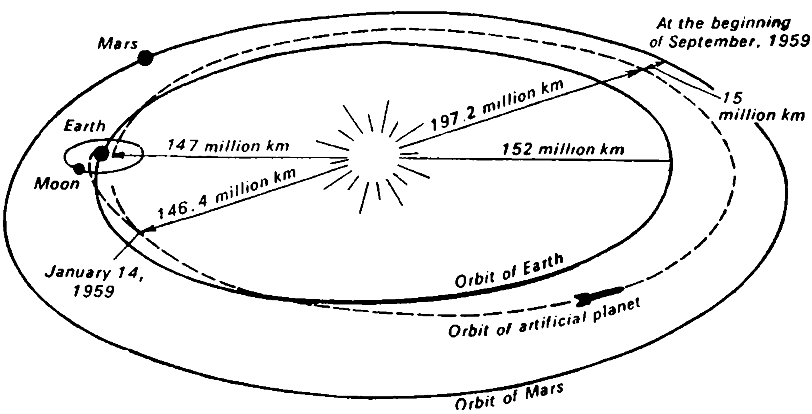
For instance, in order to achieve the earth escape velocity necessary to reach the orbit of Mars the spaceship must possess at 200 km altitude a launching speed roughly equal to 11,400 m/sec, while at 1,000 km altitude it should be 10,800 m/sec. If the spaceship is launched toward Mars from an artificial earth satellite previously placed in fixed orbit ($H = 35{,}809$ km) it is sufficient to have a speed of 5,200 m/sec.

The launching speed from earth imparted to the rocket by its engines determines the required quantity of propellant and consequently the launch weight and the size of the rocket.

Start from the orbit of a satellite

To solve the problem of flights to other planets and impart the required speed to a space apparatus K.E. Tsiolkovskii suggested the use of artificial satellites of the earth as intermediate "stations," filling stations of their kind, located in outer space on the flight routes of spaceships. Such space stations, or etheric islands as K.E. Tsiolkovskii called them, would make it possible to fill the propellant tanks of rockets during flight and thereby ensure their reaching other planets.

Interplanetary flights in such cases would take place in the following manner: A powerful multi-stage rocket would lift an interplanetary ship into space and bring it to an artificial earth satellite. There the ship would fill the propellant tanks and proceed on its way.

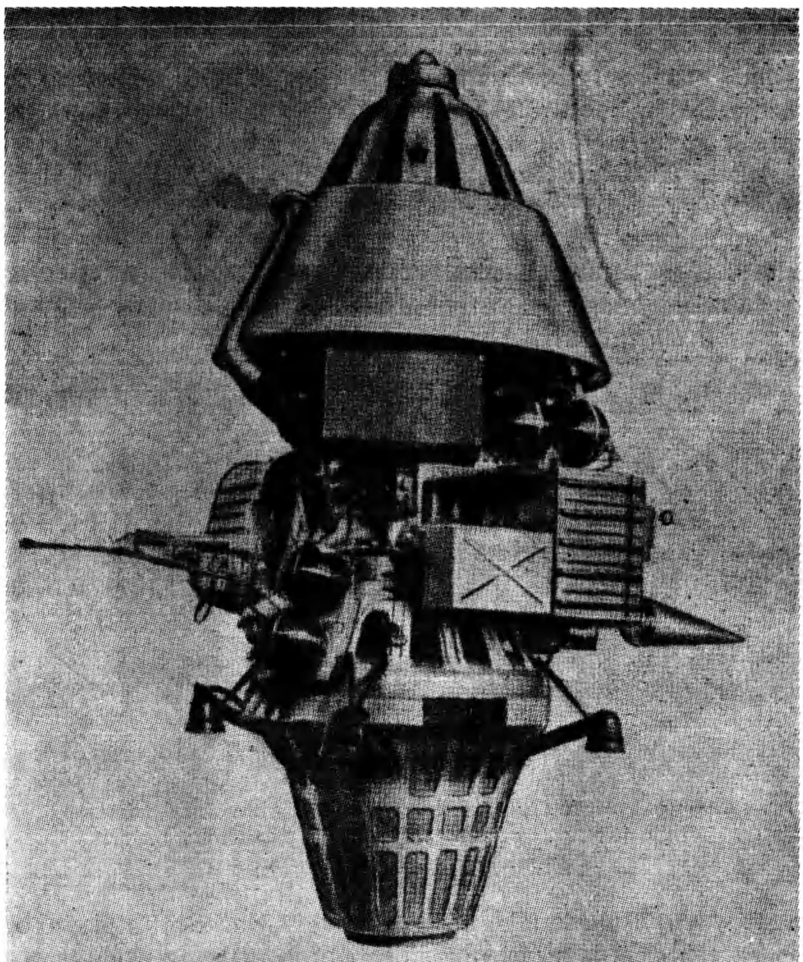


Automatic station *Luna-1*, after having flown within 5,000–6,000 km of the moon, entered orbit around the sun, becoming the first artificial planet of the solar system.

Many scientists examining the prospects of flights to other planets even think it expedient to break up the task of interplanetary flight into two independent stages. In the first the powerful launcher rockets should lift the components of the interplanetary ship, scientific equipment, propellant

storage and crew of the ship into space and put them into orbit as an earth satellite. Later the ship would proceed on its flight to Mars or Venus after being assembled in orbit.

The point of using different rockets, one for the flight from the earth's surface to the orbit as its satellite and the other for interplanetary flight, is explained by the different flight conditions for these apparatuses. The first, starting from the surface of the earth, must pass through the atmosphere and fly with substantial loading (with large acceleration). Due to this it requires a rigid streamlined casing and durable body that greatly increase the mass of the structure. The second apparatus, meant for flight in



Automatic station *Luna-12*, which became an artificial satellite of the moon.

airless space and, besides, with much less acceleration, can have a considerably lighter casing, body and engines, which makes it possible to increase the propellant storage and payload. In both cases the interplanetary spaceship would start the interplanetary voyage from the orbit of an earth satellite.

At the start from the earth satellite the spaceship needs to develop an additional speed of only 3,000–4,000 m/sec for flight to other planets, which can be carried out by means of one rocket stage.

K.E. Tsiolkovskii's idea of using artificial satellites of the earth as bases or stations to send spaceships to other planets of the solar system proved to be extremely fruitful. Today the great majority of projects for interplanetary flight are based on it. Developing K.E. Tsiolkovskii's idea one of his successors, Y.V. Kondratyuk, suggested using artificial satellites not only of the earth but also of the moon as space stations. Much research already devoted to this subject shows that this idea also deserves attention. In the future interplanetary ships will be able to leave on their distant voyages not only from the surface of our planet or its artificial satellites but also from the surface of the natural satellite of the earth, i.e. the moon, or its satellites. These ships must, or course, be prepared on earth and carried to the starting point, for instance an artificial satellite of the moon, as a whole or in parts. Nevertheless, this organization of an interplanetary flight is very rational. And the possibility of making a certain part of the load or structural element of the spaceship on the moon is probably not ruled out in the more distant future, further increasing the value of the idea.

The main advantage of starting from the moon or its satellites lies in the fact that the mass of the moon and, consequently, its gravitational force are many times less than the earth's and therefore a considerably lower speed will be required for the launching.

Orbital velocity of an interplanetary spaceship

In the problems of interplanetary flight in astronautics the speed that a spaceship must attain in space while moving from planet to planet is given first place (these speeds are so great that we will express them in kilometers per second).

It is known that the earth moves with a velocity of 29.8 km/sec in its orbit around the sun. This is the mean orbital velocity of the earth. Venus is situated nearer to the sun and its orbital velocity is 35 km/sec, more than the earth's. Mars is at a greater distance from the sun than the earth. Its orbital velocity is 24.1 km/sec. Saturn, whose orbit is situated at a distance of 1,425,647 km from the sun, moves with a velocity of 9.6 km/sec. These are the eternal orbits of the planets and eternal velocities of their movement.

So planets, i.e. satellites of the sun, show the same picture as satellites

of the earth. The farther the satellite is located from the central body, the lower the speed of its flight. This picture is the visual illustration of Kepler's law: "The square of the orbital period of a planet is proportional to the cube of its distance from the sun."

For a spaceship to move freely from one planet to another it must possess the corresponding orbital velocity. The magnitude and direction of this velocity determine the ship's course and the duration of its flight to the given objective.

The movement of interplanetary spaceships within the boundaries of the solar system obeys the same laws as the movement of artificial satellites around the earth.

If a spaceship, after escaping from the sphere of the earth's gravity, travels at a certain distance from the sun with a speed equal to the "circular" velocity for that distance and in a direction perpendicular to the solar ray it will move along a circular orbit, converting itself into an artificial planet.

For the spaceship to break out of the circular orbit and begin to move along the arc of an ellipse away from the sun its orbital velocity must be more than the circular one. For instance, if a spaceship situated in earth orbit at a distance of 149.5 million km from the sun has a velocity of 31.9 km/sec it will move along an elliptical orbit stretching further than that of the earth, and at aphelion (the point on the orbit at the maximum distance from the sun) will be 200 million km from the sun.

On the other hand, for an interplanetary spaceship to move toward the sun its orbital velocity must be less than circular. For instance, a spaceship that has a speed of 28.1 km/sec in earth orbit while moving along an elliptical orbit approaches at perihelion (the point nearest the sun) to within 120 million km of the sun.

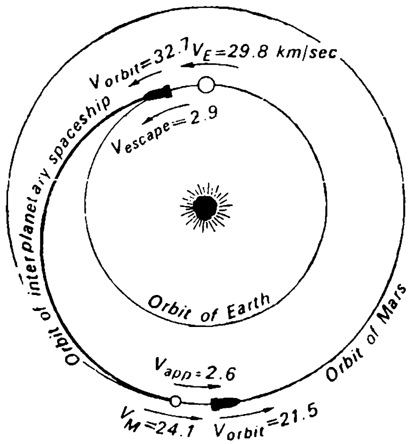
Then what speed must a spaceship have in order to reach the orbit of a given planet?

At a speed of 27.3 km/sec a spaceship moving along an elliptical orbit around the sun moves to within a distance of 108.1 million km at perihelion, reaching the orbit of Venus. At an orbital velocity of 22.2 km/sec it approaches the orbit of Mercury, passing to within a distance of 57.9 million km from the sun.

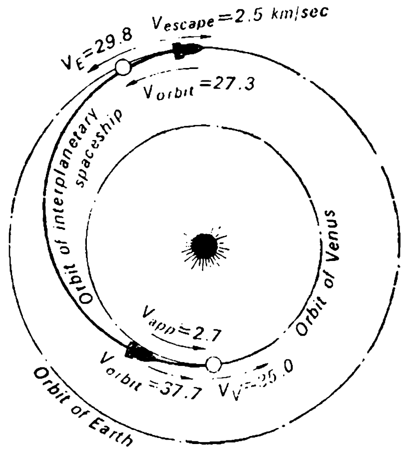
Mercury's orbit is at a distance of 227.7 million km from the sun. For a spaceship to get out of earth's orbit and reach Mars' orbit it must have an orbital velocity of 32.7 km/sec. To move still farther from the sun and reach Jupiter's orbit the spaceship needs an orbital velocity of 38.5 km/sec. Reaching Saturn requires an even larger orbital velocity of 40 km/sec. The farthest planet of the solar system, Pluto, can be reached only if the interplanetary spaceship achieves an orbital velocity of 41.6 km/sec while situated in earth orbit.

During flights to outer planets, i.e. to those planets whose orbits are

located farther from the sun than that of the earth, the spaceship must take off in the direction in which our planet is moving so that the earth escape



The orbital velocities of a spaceship during flight from the earth to Venus with minimum propellant consumption.



The orbital velocities of an interplanetary spaceship during flight from the earth to Mars with minimum propellant consumption.

velocity is added to that of the earth's movement. During the flight toward Venus and Mercury the direction of take-off of the spaceship must be chosen in such a way as to be opposite to the earth's movement.

The magnitude of the orbital velocity that a spaceship must possess in order to fly from the orbit of one planet to that of another can be calculated from the formula

$$V_{\text{or}} = V_{\text{k}1}\sqrt{\frac{2R_2}{R_1+R_2}},$$

where $V_{\text{k}1}$ is the circular velocity in the orbit of the first planet; R_1 and R_2 are the radii of orbits of the first and second planets.

If the spaceship is to fly beyond the limits of the solar system into the infinite space of the universe then R_2 in the formula considered above must be equal to ∞. The magnitude of the orbital velocity then would be $\sqrt{2}$ times that of the circular velocity $V_{\text{k}1}$. So as to fly out of earth orbit beyond the limits of solar gravitation the interstellar spaceship must have a speed of

$$V_{\text{or}} = V_{\text{kE}}\sqrt{2} = 42.1 \text{ km/sec},$$

where V_{kE} is the circular velocity in earth orbit.

Consequently its earth escape velocity will be equal to 12.3 km/sec.

The launching speed for a spaceship leaving the earth can be calculated

from the magnitude of the earth escape velocity and known magnitude of the parabolic velocity. In the above problem it is equal to 16.7 km/sec. This is the solar escape velocity. Mention was made of this velocity earlier but nothing was said about how to calculate it. We did so because to calculate solar escape velocity it is necessary to know the laws of motion of spaceships not only relative to the earth but also relative to the sun.

The velocity of an interplanetary spaceship flying along an elliptical orbit around the sun does not remain constant. It is reduced on moving away from the sun and increased on moving toward it. For instance, during a flight to Venus the orbital velocity of a spaceship increases from 27.3 km/sec near the earth's orbit to 37.7 km/sec on approaching Venus' orbit. During a flight to Mars it is reduced from 32.7 km/sec to 21.5 km/sec.

The magnitude of the speed of an interplanetary spaceship at any point of its orbit can be calculated in the same way as that of an earth satellite flying along an elliptical orbit:

$$V_{\mathrm{el}} = V_{\mathrm{k}R}\sqrt{2-\frac{2R}{R_{\mathrm{P}}+R_{\mathrm{A}}}},$$

where $V_{\mathrm{k}R}$ is the circular velocity at a distance R from the sun; R is the radius of orbit at a certain moment; R_{P} and R_{A} are the radii of elliptical orbit at perihelion and aphelion.

The speeds of a spaceship at aphelion and perihelion, i.e. at the points of the orbit farthest from and nearest to the sun, like those of the artificial earth satellites at apogee and perigee, are interconnected by a simple relation. Their magnitudes are inversely proportional to the distance of the spaceship from the sun:

$$\frac{V_{\mathrm{A}}}{V_{\mathrm{P}}}=\frac{R_{\mathrm{P}}}{R_{\mathrm{A}}}.$$

By knowing the orbital velocity of the spaceship at the moment of exit from the sphere of earth's gravity its speed at the opposite point of the orbit can easily be calculated.

Approach speed

After traveling hundreds of millions of kilometers of the space route the interplanetary spaceship at last approaches the objective of its voyage. Like the first spaceships after their flight around the earth this ship also faces the problem of ensuring a smooth and safe landing on the surface of the planet. For this it is necessary to know the speed at which the spaceship will approach the planet. The planet and the ship move along different orbits. This means that velocities also will be different at moment of meeting. The speed of the spaceship with respect to the planet, i.e. the speed with which the spaceship flying in from deep space will enter the sphere of the

planet's gravity, will be equal to the geometric difference of the orbital velocities of the planet and the spaceship. It can be calculated by the formula

$$V_{app} = \sqrt{V_{sh}^2 + V_{pl}^2 - 2V_{sh} \cdot V_{pl} \cdot \cos\varphi},$$

where V_{sh} is the orbital velocity of the interplanetary spaceship; V_{pl} is the orbital velocity of the planet; φ is the angle between the directions of the speeds of the spaceship and the planet.

If the flight paths of the interplanetary spaceship and the planet coincide, which is possible only when the orbit of the spaceship approaches that of the planet along the tangent ($\varphi = 0$), $\cos\varphi = 1.0$ and the quantity under the square root sign becomes the exact square of the difference between the two velocities $(V_{sh} - V_{pl})^2$. Consequently, in this case the approach speed is equal to the arithmetic difference of the speeds of the spaceship and the planet:

$$V_{app} = V_{sh} - V_{pl}.$$

In the examples we considered of flight from the earth to other planets with minimum propellant consumption the spaceships moved along a tangent to orbits of the planets and the approach speeds were equal to the difference between the speeds of the spaceship and the planet. For instance, the spaceship in this case moved toward Venus' orbit with an orbital velocity of 37.7 km/sec while the mean orbital velocity of Venus is 35 km/sec. The approach speed of the spaceship toward Venus was therefore equal to 2.7 km/sec. The approach speed toward Mars was 2.6 km/sec.

One more thing should be noted here. If the interplanetary spaceship is flying from the earth to Mercury or Venus its speed at the time of meeting is more than that of the planet, and while approaching it catches up with the latter. But if the spaceship is traveling toward Mars, Jupiter, Saturn or other planets situated farther than the earth from the sun and approaches their orbits along the tangent at the aphelion of its orbit (the flight with minimum expenditure of energy) its velocity turns out to be less than that of the planet. So that the approach can take place the spaceship must move toward the set orbit in advance and arrive before the planet. Then the planet with its higher speed will catch up with the spaceship. To the passengers of the interplanetary spaceship it would seem that they were flying to meet the planet.

Closing velocity

After reaching the sphere of the planet's gravity, the spaceship rushes toward the surface with increasing speed. The magnitude of the speed with which the spaceship will move toward the planet, i.e. the speed of landing of the spaceship or, better, the approach speed, is determined by the gravitational force of the planet. Had the spaceship approached the sphere of the

planet's gravity with zero speed its speed of landing would have been exactly equal in magnitude to the escape velocity for the given planet. But since the approach velocity of the spaceship is greater than zero the approach speed will also be somewhat greater than escape velocity. Like the take-off velocity it can be determined by the formula

$$V_{cl} = \sqrt{V_P^2 + V_{NE}^2}\,.$$

During landing on planets like Venus, Mars or Jupiter the approach speed or a part of it can be reduced by the resistance of the atmosphere. While landing on planets without atmosphere, for instance, Mercury, the entire approach speed must be reduced by the forces of the rocket engines.

Characteristic speed

In astronautics, in the analysis of the launching of earth satellites in connection with distant interplanetary flights, one more speed is widely used. This speed is very important in judging the complexities and possibilities of carrying out certain space flights. Whatever be the flight planned, let it be launching of an earth satellite, a flight to the moon, or sending an automatic station toward the moon or Mars, this speed is always determined. It is, perhaps, the most widely used of all cosmic speeds. Nevertheless, not a single space apparatus achieves this speed at any time. This is the "characteristic" speed.

This speed characterizes the amount of energy that is necessary to carry out a particular space flight. It is a known fact, however, that energy and speed are two different physical quantities. And energy is never measured in units of speed. So never say that the required amount of energy is equal to the magnitude of the characteristic speed. But the amount of energy is characterized by that speed which is to be attained as a result of this amount of energy. The characteristic speed is that speed which a rocket would have attained with the given amount of propellant during flight in free space, i.e. outside the sphere of gravity.

It has already been said that with increasing altitude of flight the magnitude of circular velocity decreases. But decreasing circular velocity when moving away from the earth does not at all mean that less energy is needed for the launching of a distant satellite than for a nearby one. On the contrary, the amount of propellant in a rocket increases with the increasing flight altitude of a satellite. And this is fully understandable. Indeed, it is necessary to account for the energy that is required not only for accelerating the satellite but also for its climb to high altitudes.

In order to determine the amount of energy that must be spent to lift a satellite to a certain altitude and convey the required velocity to it, i.e. the total amount of energy required to put the satellite into a given orbit, the characteristic speed is used.

The magnitude of the characteristic speed necessary for launching an earth satellite into circular orbit can be calculated by the formula

$$V_{\text{char}} = V_{K0}\sqrt{2 - \frac{R_0}{R_0 + H}}.$$

For instance, for an altitude of 200 km, where the circular velocity is equal to 7,791 m/sec, the characteristic speed is 8,031 m/sec. For 1,000 km the difference between circular and characteristic speeds increases. Here their magnitudes are 7,356 m/sec and 8,431 m/sec respectively. For a fixed one-day orbit the magnitude of the characteristic speed equals 10,758 m/sec, i.e. exceeds the circular velocity by more than three times.

Characteristic speed is also used in computing distant interplanetary flights. Let us consider, for example, a flight to Mars. To bring off such a flight the rocket must develop a velocity of not less than 11,570 m/sec at launch from the earth. On approaching Mars it is necessary to reduce the speed of the spaceship so that it is not destroyed on landing. Let us assume that the necessary reduction in speed is 5,000 m/sec. And, as is known, from the point of view of spending energy it is immaterial whether the speed of the spaceship is increased or decreased. Only the magnitude of the necessary variation is important. On taking off from Mars to return to the earth's orbit it is necessary to develop a speed of 5,700 m/sec. And finally, on landing on the earth the flight of the spaceship must again be decelerated by, say, 3,000 m/sec. Thus during a flight earth-Mars-earth the spaceship must several times fire its rocket engines to change speed. The total variation in the speed in the example considered is 25,270 m/sec. In this connection the required propellant flow rate will not be at all affected by the operational regime of the engine, i.e. whether the engine would work continuously and convey the set speed to the space apparatus flying in free space all at once or would be fired several times, conveying the same amount of speed in several quantums. Consequently, in order to perform the flight to Mars and return to earth the space apparatus needs to spend as much energy (i.e. to spend so much propellant) as is necessary to develop a speed of 25,270 m/sec. The sum of all increments and reductions in speed to be transmitted to the space apparatus during flight is also called characteristic speed.

The magnitude of the characteristic speed in interplanetary flights depends not only on the route but also on the trajectory chosen and on the extent to which the planetary atmosphere is used for decelerating the apparatus. To perform interplanetary travel in as short a time as possible it is necessary to increase the speed of the spaceship at take-off from the earth and accordingly increase the characteristic speed. On the other hand the magnitude of the characteristic speed is decreased by using a design of spaceship (for instance, with wings or a powerful parachute system) that

makes it possible during the approach to eliminate a considerable part of the speed with the help of the resistance of the air or any other gas surrounding the planet, while only negligibly decelerating the spaceship with the rocket engines.

Therefore the figure mentioned above can be considered as a possible example of characteristic speed for the route earth-Mars-earth.

We will indicate one more factor that is taken into acconnt in determining the magnitude of the characteristic speed. During take-off from the earth the rocket needs to overcome gravity and air resistance in the process of accelerating. Clearly, the rocket in this case attains less speed than during flight in free space for the same propellant flow rate. And to attain one and the same velocity a larger quantity of propellant is required.

During launching of artificial earth satellites, according to data in the literature, a quantity of propellant is spent in overcoming air resistance and gravitational force that would have made possible further increase in the speed of the rocket by 1,000–1,500 m/sec. Therefore, the magnitude of the characteristic speed for launching an earth satellite calculated by the formula given above should be increased by 1,000–1,500 m/sec. As a result, it turns out that to launch an earth satellite to an altitude of, say, 200 km, the magnitude of the characteristic speed is 9,000–9,500 m/sec.

The analogical increase of characteristic speed needs to be carried out also for interplanetary space apparatuses starting from the earth.

SPACE ROCKETS

The construction of a space rocket

In his classic work *Investigation of Outer Space by Jet Devices* K.E. Tsiolkovskii wrote:

"...I suggest a jet device, i.e. a type of rocket, but a grandiose and specially constructed one, as an atmosphere probe."

How are the rockets embodying Tsiolkovskii's ideas constructed?

Modern rockets intended for flights within the limits of the atmosphere, and also those designed to fly off into airless space, but to be launched either from the earth or from a flight vehicle in the dense layers of atmosphere, have a streamlined cigar-like shape. To reduce the air resistance designers try to make the diameter of the rocket as small as possible and to accommodate the necessary payload and propellant storage in the body *1* by increasing its length. The majority of rockets built so far have a length equal to 10–15 times their diameters.

In the tail section of the rocket there are sometimes air vanes for flight stabilization and control during its movement in the atmosphere.

The main part of the rocket is the engine *4* which consists of a combustion chamber with nozzle, turbo-pump unit *3* and the starting and control-

ling equipment of the engine. Usually, as in all modern rockets, the power plant is located in the tail section of the rocket body.

The tanks *5* with fuel and oxidizer occupy a large portion of the rocket body. At the present level of engineering art it is possible to design rockets that accommodate propellant accounting for 80–90% of the rocket's total weight.

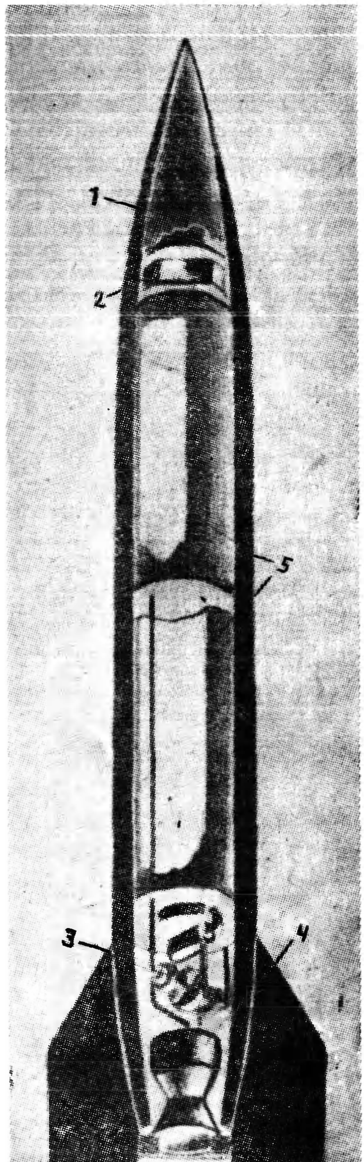


Diagram of a rocket with liquid-propellant rocket engine.

The most important element of modern high-altitude and long-range rockets is the control equipment which ensures stable movement of the rocket and flight in the desired direction. For these objectives the rocket carries an autopilot which maintains its linear motion and a programming mechanism, if it is necessary to change the flight direction several times during flight according to prearranged plan. On many rockets radio equipment is installed, making it possible to influence the flight from the ground by transmitting the appropriate signals.

The control equipment, operating automatically or under the influence of the signals from the ground, acts on the special steering engines which deviate the rudders to give the required flight direction to the rocket. While moving through the dense layers of the atmosphere the air vanes can provide effective control of the rocket. But at high altitudes, in rarefied layers of air, and still more in airless space, these vanes turn out to be useless.

For controlling the rocket under these conditions, K.E. Tsiolkovskii suggested the use of jet vanes, which are heat-resistant vanes that can be located in the jet of the exhaust gases of the engine. On turning such vanes part of the gaseous jet is deflected to one side, exerting pressure on the

surface of the vanes. The force due to gas pressure on the vane builds a moment that tends to turn the rocket about its center of mass, i.e. to change the direction of flight. Nowadays on high-altitude and long-range rockets Tsiolkovskii's vanes are often used.

If several engines, and not one, are mounted on the rocket, to hold it strictly vertical or to change its direction it is possible to achieve this by controlling the thrust of the engines. Due to the difference in magnitudes of thrust of the engines located on different sides with respect to the axis of the rocket its body turns accordingly.

The control of the rocket can also be carried out with the help of one engine mounted on a hinge. When it turns the direction of the thrust is changed, causing the rocket to turn correspondingly.

Lastly, one must provide space to accommodate the payload, i.e. equipment for scientific research and cabins for the people in passenger rockets.

The building of a space rocket is a large complex of scientific-technical assignments. First of all it is necessary to choose the most advantageous external shape for the rocket. Before entering airless space the spaceship must pass through the earth's atmosphere. Therefore an aerodynamic shape must be given to it such that air resistance will be minimal. It must be noted here that with the increasing dimensions of spaceships the part of the energy spent on overcoming air resistance decreases. Nevertheless, the task of reducing air resistance will always confront the designers of space rockets.

The aerodynamics of rockets is not confined to the problem of air resistance. It is necessary to determine the forces caused by air pressure on various elements of the rocket body in order to design the structure for rigidity. Many rockets, like aircraft, will have air vanes for controlling flight while moving through the atmosphere and sometimes small wings also. This means that the appropriate dimensions and shapes for the wings and vanes have to be chosen.

While building a space rocket one more important aerodynamic problem confronts us: protection from excessively high temperatures. It is known that during flight in the atmosphere at high supersonic velocities the walls of the flight vehicle are fiercely heated due to air friction. If the flight speed exceeds the speed of sound by three times the temperature of the walls can go up by 300°C. With a further increase in flight speed the temperature of the gas in front of the rocket's nose steeply increases and at a speed of nearly 7 km/sec attains 8–10 thousand degrees.

For a spaceship not to become a meteor, which burns out while moving through the air, it is necessary to choose a flight regime where the maximum speeds are attained beyond the limits of the atmosphere or in its more rarefied layers. It is necessary to use materials for the outer casing of the

rockets capable of withstanding high temperatures. In a number of cases it becomes necessary to employ artificial cooling of the cabin, for instance, cooling by the propellant used for operating the engine or with the help of special installations.

A protective coating on the nose of space apparatus is widely used. This is destroyed (vaporized) under the action of high temperatures but protects the walls of the apparatus for the short duration of its movement through the atmosphere at high speed.

For the flight in airless space it is necessary to protect the astronauts from both excessive heating by solar rays and the cold of outer space where the temperature, as is well known, is near $-273°C$. This problem can be solved by thermal insulation of the cabin.

Spaceships intended to move only in airless space will, naturally, have other external shapes than rockets that have to negotiate the atmosphere. It is not essential to give these spaceships good aerodynamic shapes. They can have just a structural frame with a cabin, propellant tanks and engine unit mounted on it not covered by any external casing.

On some spaceships large parabolic mirrors are mounted to make use of solar energy.

The problem of materials for spaceships is of exceptional importance. While light and durable alloys were required for successful development of aviation in building spaceships this problem becomes even more acute.

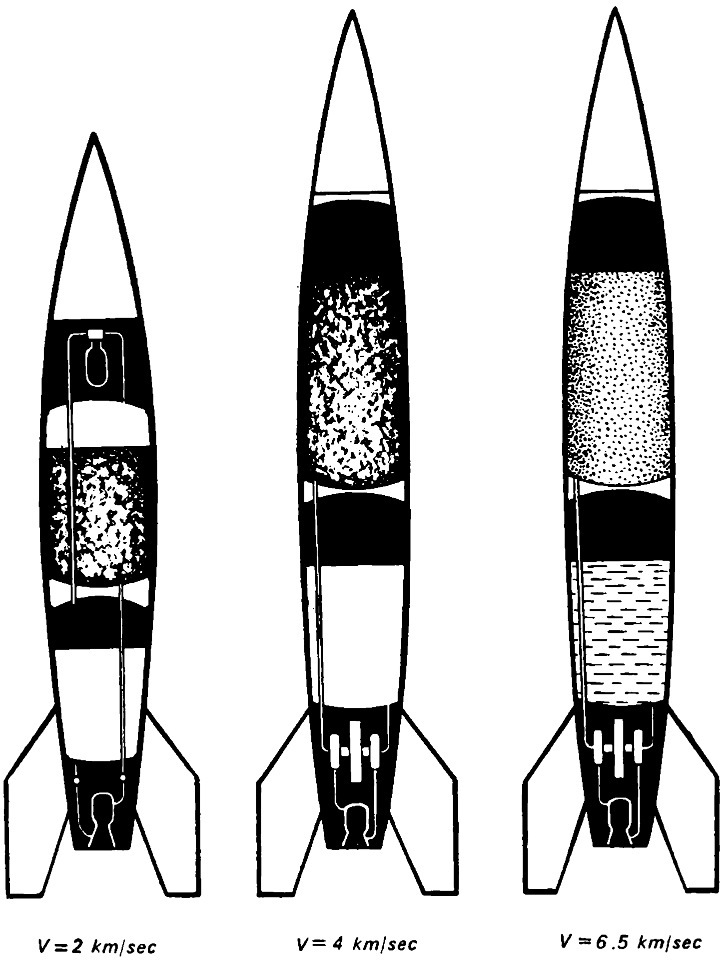
A reduction of only 1 kg in the weight of a rocket intended for a flight to Mars and back results in saving 2 tons of propellant. This shows how important it is to create even lighter and stiffer alloys for space rockets than those used in aviation. Great help to the designers of rockets comes from the metallurgists working out new, more rigid and particularly heat-resistant and vibration-resistant alloys.

Not only the development of new materials but also their rational use in the construction of the space rocket is of paramount importance. The art of designing must play a large part in the building of interplanetary spaceships. In designing every part of the rocket, every unit, there is a sustained struggle to reduce its weight. M.K. Tikhonravov, designer of the first Soviet liquid-propellant rocket, said to his students: "We must be jewelers in our work," dramatizing with these words the intensive struggle to reduce weight.

To produce highly durable, light structures, further development of the techniques of designing for strength is needed. This is where the works of the specialists on the theory of elasticity come in, equipping designers with the most accurate methods of designing rocket structures for strength. Among them are the works on the theory of thick-walled shells and the theory of resisting vibrations. The development of theory and the accumulation of empirical data on the strength of materials under varying

temperatures is also necessary: from the hundreds and thousands of degrees typical for the outer shell of a fast-moving rocket and the combustion chamber of rocket engines to temperatures close to absolute zero, which certain structural elements of the rocket will face during flight in outer space.

The problem of building a spaceship is not confined to construction of



The speed of a rocket depends on its structural perfection and the quality of the propellant used. The first rocket has a heavy body and the propellant is 55% of the launch weight. The jet velocity is 2,500 m/sec. The second rocket has a more sophisticated structure and the weight of the propellant accommodated in the tanks is 80% of its launch weight. On using the same propellant this rocket attains twice the flight speed of the first rocket. In the third rocket, propellant of better quality is used, allowing an increase in jet velocity to 4,000 m/sec. The propellant stock makes up 80% of the launch weight. It attains an even higher flight speed.

highly efficient engine and rocket body. It is also necessary to mount a large number of instruments and automatic equipment for the flight of the spaceship, its control, communication with earth, maintenance of vital conditions for the crew and completion of scientific experiments in flight and on achieving the target of the expedition.

Besides the propellant stock a spaceship must accommodate food, water and oxygen for the passengers for the duration of travel in outer space. For every man for one day roughly 1.25 kg of food, 2 liters of water and 1.25 kg of oxygen is necessary. This means that for a flight to Mars of nearly two-and-one-half years' duration more than 4 tons of load is necessary to keep each man alive.

To sustain the lives of people in space it is necessary to provide them with more than food. The cabin of a spaceship flying in airless space is equipped with a variety of apparatus, devices and equipment to create the conditions necessary for human life. This first of all includes the apparatus that maintains the required pressure, temperature, humidity and chemical composition of the air. In building the cabin of a spaceship particular attention is paid to shielding the crew from the dangerous effect of radiation coming from the sun and from outer space.

During the flight of a spaceship tens and hundreds of instruments measure the parameters of the surrounding medium, observe the functioning of the apparatus, measure the indices of the vital functions of the crew and other biological quantities. The results of all these measurements are transmitted to earth. This is done with the help of a radiotelemetry system. It converts instrument readings into radio signals and sends them to earth. The receiving stations pick up these signals and record them on the tapes of oscillographs.

All that has been said so far gives an idea only of the principle of construction of a liquid-propellant rocket and its scheme. In reality the construction of a rocket is much more complicated. Modern cosmic rocket systems are the most complicated machines, absorbing the latest achievements in almost all fields of science and engineering. Each of the elements of the rocket, each of its aggregates, is the most complicated engineering feat. A large number of specialists work many years on its creation. Basic courses are devoted to their description, to setting forth the methods of calculation and design. Construction of the basic elements of the rocket, its aggregates and equipment, differs for different types of rocket and is moreover continuously modified.

This book sets itself the task of describing in brief the basic problems of rocket engineering and of presenting the latest in the science of flight vehicles that characterizes the cosmic rocket system.

Among the problems that most distinctly characterize cosmic rocket systems it is first necessary to elucidate the problem of rocket energetics, to

describe the power plants of space rockets lastly, to go over the principles of the spaceship.

Energy of space rocket

One of the basic technical problems whose solution by our scientists and designers opened the way to the cosmos for humanity is that of rocket energetics.

The engines of the rockets which put the spaceship *Vostok* and *Voskhod* into orbit developed a power of 20 million hp. This is three times more than the power of the greatest hydro-power plant on earth at Krasnoyarsk. The power of the engines of each of the rockets that put the artificial satellites *Proton* into orbit reached 60 million hp.

And indeed this is only the beginning. Further development of space rocket engineering will bring into being even more powerful power plants. Even now rocket engine units producing a thrust of 4,000–5,000 tons are described in foreign literature. While operating in the first stages of space rockets they would develop power up to 200 million hp.

Space flight is first of all a gigantic energy problem. Building of artificial earth satellites, launching of rockets to the moon, Venus and Mars, realization of orbital flights by man are the majestic steps of Soviet science on the stairway of rocket energetics.

Every mode of transport has been developed on the basis of appropriate power plants. The creation of reciprocating gasoline engines capable of developing tens of horsepower with small size and weight opened the way to the development of the automobile. Aircraft piston engines with a power of hundreds of horsepower were the energy base for subsonic aviation. The sonic and supersonic aircraft appeared after turbo-jet engines developing useful, so-called thrust, power of tens of thousands of horsepower were built.

The creation of engines for space rockets was a new take-off point without precedent for transport energetics. The first spaceship in the world, the *Vostok*, was put into orbit by a rocket whose engines developed 20 million hp. This means that space flights thereby signified a thousandfold increase in the power-to-weight ratio of flight vehicles.

During the Patriotic War our aviation industry was producing up to 55,000 aircraft per year. The power of the engines of this air armada was tremendous. But all these tens of thousands of single and multi-engine aircraft in their overall power were weaker than the six launcher rockets of the first spaceship *Vostok*.

To accomplish flight to other planets it is essential to perform a huge amount of work. A similar amount of energy is also required.

It is also necessary to account for the energy spent in overcoming air resistance and the force of gravity during the acceleration period in lifting and accelerating the body of the launcher rocket and that part of the pro-

pellant stock which is spent not during the initial period after launching but during the active phase of the flight, particularly the last seconds of acceleration when the speed is approaching the cosmic. As a result it turns out that the overall energy losses exceed by 10–20 times the energy obtained by the space vehicle. Consequently the launching of every kilogram of useful load into space costs a huge amount of energy loss. And while launching a multi-ton spaceship the required amount of energy increases a thousand times.

For instance, for the flight of three persons to Mars or Venus a spaceship weighing roughly 30 tons is needed. This figure refers only to an interplanetary spaceship with astronauts, scientific equipment, stocks of food, water and oxygen. And for spaceships to enter outer space, to move away from the earth to land on the planets, to take off from their surface and return to earth powerful rocket systems are essential. Their weight exceeds that of the cabins of the spaceships by many times. A rocket apparatus weighing 1,000–1,500 tons must be sent on the voyage to Mars from the orbit of an earth satellite. Of this weight only 30 tons is the useful (payload) load, which is the interplanetary spaceship. The reminder consists of propellant tanks, engine and the structural chassis connecting together all the structural elements of the apparatus.

These figures which, of course, will be modified with time, enable us to imagine the order of energy resources required of space rocket engineering for interplanetary flight.

Rocket engine

The main part of a rocket engine is the combustion chamber. The chemical energy of a propellant released during combustion is absorbed by the gaseous products of combustion which are thereby heated to high temperatures. The more the energy released by a propellant, the higher the temperature of the gas formed in the chamber. In many rocket engines it reaches 3,000–4,000°C. Gas heated to such a temperature tries to expand and to occupy the largest possible volume. Anyone who has learned physics knows that the volume of gas increases in proportion with the temperature. But the combustion chamber walls resist the expansion of the gas. And the gas compressed in the volume of the small chamber exerts pressure on its walls. In some powder rocket engines the gas pressure reaches 200–300 atm.

The resultant of the forces due to the gas pressure on the chamber walls is the thrust of a rocket engine.

In order to increase the thrust it is necessary to build the largest possible pressure. For this it is necessary to increase the rate of propellant feed and choose a propellant such that the largest quantity of energy will be released during its combustion and the gases formed will have the largest volume. For efficient operation of a rocket engine, therefore, it is necessary to

have a propellant with the maximum store of chemical energy.

Before Tsiolkovskii only powder rockets were known. Although powder is capable of releasing the energy contained in it extremely fast it severely lags behind many liquid propellants so far as quantity of energy is concerned. A kilogram of powder releases about 1,000 cal of heat during combustion. But the calorific value of benzine, for instance, is 10,500 cal per kilogram. True, the combustion of benzine needs oxygen—nearly 3.5 kg per kilogram of benzine. But even after accounting for the oxygen, or other oxidizer spent, a liquid propellant gives a larger thermal effect than powder.

The greatest merit of K.E. Tsiolkovskii, the founder of the theory of interplanetary communications, is that he treated rocket energetics as the main problem and gave all his attention to the task of choosing a propellant for the engines of interplanetary spaceships. To him belongs the idea of building a rocket engine working on a liquid propellant.

The amount of chemical energy released during combustion of a propellant determines the magnitude of the engine's nozzle exit velocity. And this in turn determines the magnitude of thrust of a rocket engine. According to the third law of mechanics the chamber walls exert on the gas the same force as the gas exerts on the walls. The gas pressure on the engine walls creates a thrust power impulse which is the reason for the forward motion of the rocket. At the same time the gas, having obtained an impulse equal in magnitude but opposite in direction, rushes out of the engine at high velocity. The magnitude of the gas velocity is closely related to the magnitude of the power impulse. Therefore by knowing the gas exit velocity it is possible to determine the force with which the chamber walls act on the gas, and the gas on the chamber walls, i.e. the magnitude of thrust of the rocket engine. The thrust is equal to the product of the mass of gas flowing out of the engine per second and its exit velocity

$$P = mW,$$

where m is the mass of the gas flowing out of the rocket engine per second; W is the exit velocity of the gas.

This means that the higher the velocity of the gas, the larger the thrust of the engine at constant flow rate of the gas. Evidently, in order to increase the engine thrust it is advisable to increase the exit velocity of the gas and not the mass, i.e. it is advisable to use a propellant with a larger content of chemical energy and not to increase its flow rate. Thus the exit velocity is a distinct indicator of the perfection of a rocket engine. It characterizes the thrust a rocket engine develops per unit mass flow rate of the propellant.

In theoretical research and in designing new rocket engines it is very difficult to calculate the exact value of the thrust on the basis of gas pressure. But the exit velocity is calculated quickly and easily. Knowing it and the propellant flow rate it is possible to obtain the magnitude of the thruts.

For this reason all calculations of the thrust characteristics of rocket engines are based on the exit velocity of gas.

This is why, in speaking about a rocket engine, the magnitude of the exit velocity of the gas is first specified. This and the total thrust are the main specifications of a rocket engine.

The exit velocity of gas characterizes the level of development of rocket energetics. In the rocket engines built at the beginning of the 30s, both in our country and abroad, the exit gas velocity was roughly 2,000 m/sec. For instance, ORM–65, one of the best Soviet engines of that time, had an exit gas velocity of 2,100 m/sec. In assessing the prospects of rocket engineering a velocity of a magnitude of 4,500 m/sec and above has been indicated in the literature.

The magnitude of the exit gas velocity plays an important role in increasing the efficiency of rockets.

Let us consider a single-stage rocket with launch weight of 100 tons designed to attain a velocity of 3 km/sec. We will assume that the structural quality of this rocket is such that the propellant weight is 80% and the structural weight 20% of the weight of the rocket (without considering the payload compartment). If the exit gas velocity in such a rocket is taken to be 2,000 m/sec it will be able to lift a payload of 3 tons—only three per cent of the launch weight. But if we use a better propellant and obtain an exit velocity of 4,000 m/sec then, other things being equal, the rocket lifts a payload of 33 tons. This is a huge difference. Alternately, with the same payload the flight speed of the rocket can be increased twofold. For ballistic rockets (missiles) it results in increasing the distance covered by the rocket from 1,000 to 5,500 km.

We will consider one more example. Let us assume that a heavy artificial satellite is put into orbit around the earth at an altitude of 200 km. A single-stage space rocket weighing 100 tons is launched from it. It must increase its velocity by 4 km/sec in order to attain a velocity of 11.8 km/sec and fly to Venus orbit in 80 days. Let us assume that the structural quality of the rocket is such that 90% of the weight of the rocket is accounted for by the propellant and 10% by the structure (without considering the payload compartment). If the exit velocity of the gas in such a rocket is, say, 2,000 m/sec then the payload is limited to 4 tons. But if we use a better propellant and obtain an exit velocity of 4,000 m/sec then, other things being equal, the rocket will carry a payload of 30 tons to Venus orbit. These examples show how important research in the field of propellant chemistry is for rocket engines.

Maximum calorific value is not the only requirement for a rocket engine propellant. The working capacity of a gas depends on its temperature, pressure and specific volume. Consequently it is essential that the products of combustion of propellant have not only high temperature but also the lar-

gest possible volume, or more precisely, minimum molecular weight. Also important are such characteristics as safety in use and storage, cost, the possibility of mass production, etc.

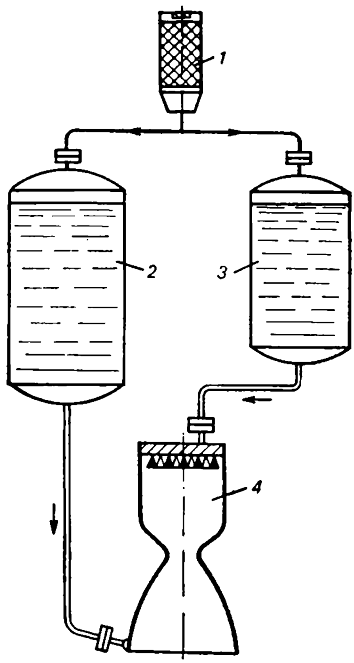


Diagram of a liquid-propellant rocket engine with pressure feed system:

1—cartridge-pressure accumulator; 2—oxidizer tank; 3—fuel tank; 4—combustion chamber.

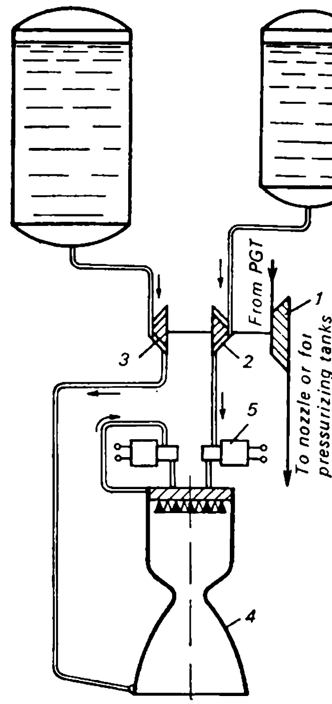


Diagram of a liquid-propellant rocket engine with pump feed:

1—turbine; 2—fuel feed pump; 3—oxidizer feed pump; 4—combustion chamber; 5—valve.

The selection of a propellant is only the beginning of the work of building a rocket. The designers face the problem of fully utilizing the chemical energy of the propellant, of obtaining in practice in the engine the calorific value that it is capable of producing during combustion, i.e. it is necessary to carry out complete combustion.

To provide complete combustion in rocket engines has turned out to be one of the most complicated problems. The conditions of propellant combustion in these engines differ essentially from those in the fire-boxes of steam boilers or in the cylinders of piston engines. A rocket engine is capable of producing a huge amount of work in a small space. The reason for such high efficiency is the exceptionally high thermal stress of the combustion chamber, exceeding in magnitude anything that had previously been

encountered in engineering. In the most sophisticated steam boilers 15 calories are released per second per liter in the fire-box as a result of burning the fuel, in reciprocating aircraft engines it is roughly 30 cal, while in liquid-propellant rocket engines it is 1,000 cal or more.

This high thermal stress can be obtained only by an extremely high rate of combustion process. The sojourn of propellant particles in the combustion chamber of certain types of liquid-propellant rocket engine is only a thousandth of a second. The vaporization, activation and complete combustion of the propellant must take place during this period. Therefore the building of rocket engines required a thorough study of the kinetics of chemical reactions and research on means of providing complete combustion at a fast rate of reaction.

The provision of an efficient combustion process and construction of a combustion chamber are the most important problems in the construction of rocket engines. To solve these problems the study of combustion processes is essential. Most scientific collectives are working on the solution of this problem. The collectives of Soviet scientists working under the guidance of academicians N.N. Semenov, L.N. Khitrin and A.S. Predvoditelev, all associate members of the Academy of Sciences, USSR, and many others have made very valuable contributions to the science of chemical reactions, and, in particular, combustion processes.

The exit velocity can be increased by increasing the pressure in the combustion chamber. For this a propellant feed system and an engine control system that will operate reliably at high pressure are required. The larger the amount of heat released in the combustion chamber, the higher the pressure of gas in it and the more complicated the task of building the fireresistant structure of the engine. The cooling of the walls at a tempera ture of 3,000–4,000°C is a serious engineering-physical problem.

Rocket engines possess a typical property that distinguishes them from the other heat engines. It is known that engines of reciprocating (piston) and rotary (turbine) type transmit the energy received from gas to a shaft which rotates a certain intermediate mechanism (propeller, wheel). These engines develop roughly constant power at the shaft at constant fuel consumption irrespective of the speed of the automobile or ship on which they are mounted. But a rocket engine at a particular propellant consumption maintains a constant magnitude of thrust. Its power here is equal to the product of the thrust and the flight speed:

$$N=\frac{PV}{75}\ \text{hp},$$

where P is the thrust of the rocket engine in kg; V is the flight speed in m/sec.

This means that the power of a rocket engine grows in proportion to the velocity of the rocket. The faster the spaceship travels the larger the useful

power of the engine.

This prime property of a rocket engine determines the conditions for its efficient application. Let us try to compare a rocket engine with a reciprocating diesel engine.

Let us assume that diesel engines with a total power of 100,000 hp have been installed on an ocean tanker (vessel for transporting oil) of 30,000 tons. They transfer to the tanker a velocity of 20 knots, i.e. nearly 10 m/sec. For their operation the engines consume about 20 tons of diesel fuel per hour, or slightly less than 6 kg per second. If a rocket engine of the same power were to be installed in the tanker its thrust would be 750 tons. It would consume nearly 3 tons of liquid-propellant per second, or 10,000 tons per hour, i.e. 500 times more than that consumed by the diesel engines. The tanker with rocket engines would stop after moving only 70 km from the shore since its engines would have gulped in two hours all the propellant this ship could carry.

Indeed, at small displacement velocities rocket engines turn out to be the least economical of all. That is why in the years when only ships, trains, automobiles and subsonic aircraft were being built the use of rocket engines was technically pointless. But when science began to master space, when the building of flight vehicles of colossal velocity was required, the picture was suddenly changed. Rocket engines proved to be the most efficient ones. Firstly, because they are the only engines capable of operating in airless space; and secondly, because they are the lightest of all engines. But, besides this, so far as fuel consumption at large flight speeds is concerned they can compete with reciprocating engines.

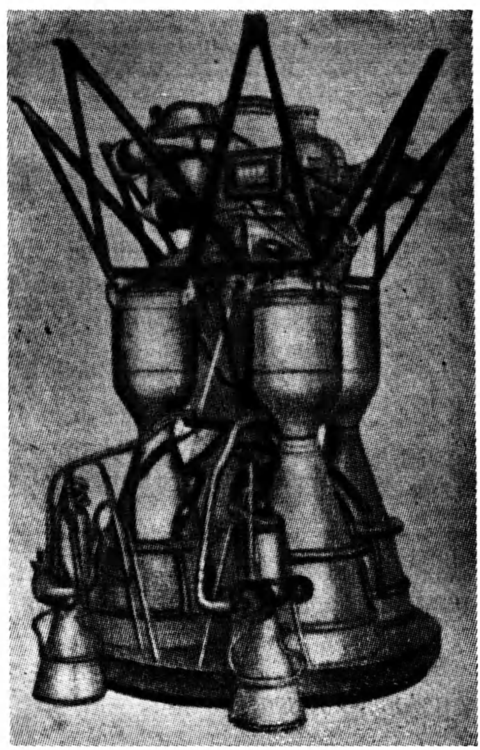
Let us take the same rocket engine with the thrust of 750 tons and mount it on the first stage of a space rocket. Let us assume that this stage attains a velocity of 3 km/sec. At such a flight speed the power of the engine considered would be 30 million hp. The fuel consumption remains the same as before. Here the rocket engine would spend not 500 times more propellant, but only twice as much as that consumed by a diesel engine on locomotive or a ship per unit hp. Let us install the same rocket engine in the last stage of a rocket flying to Mars. Its velocity must be equal to 11.6 km/sec. At this velocity the engine will develop a power of 116 million hp while the propellant consumption remains the same as before. And the rocket engine will be twice as economical as the diesel engine.

The rocket engine is an engine of the highest speeds. K.E. Tsiolkovskii has proved theoretically that the efficiency of rocket flight vehicles increases with increasing flight speeds and reaches a maximum value when the flight speed becomes equal to the exit velocity of the gas.

The notable liquid-propellant rocket engines of Soviet space rockets are graphic examples of successful solution of the problem of rocket engine construction.

On the first stage of the rocket *Vostok*, which from 1957 was so successfully used for investigating outer space, four RD–107 engines were mounted. Each of them developed a thrust of 102 tons, the specific impulse was 314 sec, the pressure in the combustion chamber equaled 60 atm, the degree of expansion in the nozzle was 150.

The RD–107 engine was of four-chamber construction with two steering chambers operating on the components of a propellant from one turbo-pump aggregate. Multi-chamber construction made it possible substantially to reduce the length of the engine, which resulted in decreasing the weight of the rocket. The turbo-pump aggregate had two main centrifugal pumps (for oxidizer and fuel) and two auxiliary pumps driven through a speed increaser (to feed hydrogen peroxide to the gas generator and liquid nitrogen to the pressure charging system of the propellant tanks). For vaporization of liquid nitrogen in the turbo-pump aggregate there was tubular heat exchanger heated by a mixture of steam and gas produced in the turbine. The turbine was driven by the products of dissociation of hydrogen peroxide by a solid catalyst in the gas generator. The mixture of steam and gas



The four-chamber liquid-propellant rocket engine RD–107
of the first stage of the rocket-launcher *Vostok*.

produced in the turbine was thrown out through a manifold, building additional thrust.

The combustion chambers are cylindrical with plant injector head. The main chambers have an internal diameter of 430 mm. The diameter of the critical section of the nozzle is 166 mm. The thrust chamber is a welded structure. The fire-side wall of the chamber at the most thermally stressed part is made of bronze with milled ribs fixed at the apex to the external power jacket by high-temperature soldering. At less stressed places the bronze fire-side wall is soldered to the jacket through corrugated packing that provides the channels for the flow of fuel, replacing the ribs. This construction makes it possible to build a chamber of small weight for high pressure and large heat flows.

The duplex bronze burners ensure complete combustion of the propellant. The cooling of the chambers by fuel is direct-flow regenerative with the internal curtains formed by the peripheral row of burners. The combination of external and internal cooling and the use of good heat-conducting walls made of bronze guarantee reliable cooling of the chamber at high combustion temperatures and significant pressure of gases.

Swiveling steering chambers are used to control rocket flight. Starting, operational control and stopping of the engine are carried out automatically by command from aboard the rocket. The ignition is pyrotechnical with electrical signals and interlocking. The starting of the engine is accomplished through the pilot stage of thrust in the process of which the components of the propellant are delivered to the combustion chambers under pressure from the pressurized propellant tanks of the rocket. The changeover to the main stage of thrust is carried out automatically by putting the gas generator into operation. The variation of thrust and ratio of propellant components in flight is achieved with engine regulators on command from the flight control system and the system of tank discharge.

The construction of the second stage of the RD–108 engine of the rocket *Vostok* is similar to the one described. The basic differences are: four steering chambers, different aggregates of automation due to a different scheme of starting and stopping and large resources, since the RD–108 engine is switched on during launching of the rocket together with the engines of the first stage.

The RD–107 and RD–108 engines were developed during 1954–1957. Launcher rockets with these engines and their modified versions ensured the successful flights of many artificial satellites of the earth, moon and sun, despatch of automatic stations to the moon, Venus and Mars and the manned spaceships *Vostok*, *Voskhod* and others.

The first representative of the varied launcher rockets of the *Cosmic* series was the two-stage rocket that undertook its first space journey on March 16, 1962.

On the first stage of this rocket is mounted the RD–214 engine with 74 tons thrust in vacuum. This is the first powerful serial engine in the USSR operating on fuming nitric acid as oxidizer and refined products of kerosene as fuel. The engine develops the largest thrust and has the largest specific impulse (264 sec) among the known engines of that type working on nitric acid (oxidizer) and hydrocarbon fuel. The pressure of gas in the chamber is 45 atm and the degree of expansion of gases in the nozzle is 64.

The RD–214 engine is a four-chamber one with common turbo-pump aggregate that includes turbine, centrifugal pumps for oxidizer and fuel (one each) and a pump to supply hydrogen peroxide to the gas generator. The products of catalytic dissociation of the hydrogen peroxide in the gas generator are used to drive the turbine.

The mixture of steam and gas produced in the turbine is thrown out through a nozzle which builds additional thrust. Cooling of the chambers, of the regenerative type, is by the fuel and internal screens formed by the peripheral burner heads of the combustion chamber. The internal diameter of the combustion chamber is 480 mm and the throat diameter of the nozzle is 176 mm. Ignition is chemical: the fuel is self-igniting in combination with the main oxidizer. The starting fuel is sprayed in the main manifold before the fuel pump starts up. Starting takes place without any intermediate stage.

Regulating thrust in flight is achieved by varying the flow of hydrogen peroxide to the gas generator. Switching off the engine is achieved through the last stage. Thrust vector control is carried out with the help of jet vanes.

The RD–214 engine has been flying from 1957 on the prototype of the rocket *Cosmos* and belongs to the early period.

On the second stage of this launcher rocket the RD–119 engine with 11 tons thrust is mounted. It works on oxygen-dimethyl-hydrazine propellant (asymmetrical dimethylhydrazine). It was built in 1958–1962. The pressure of gas in the combustion chamber is 80 atm. During the process of gas flow its pressure decreases 1,350 times and at the nozzle exit section it is roughly 0.06 atm. Due to this large pressure drop it is possible to convert almost all the potential energy into kinetic energy and obtain high exit velocity. The RD–119 engine has a specific impulse of 352 sec in vacuum. This is the highest value for oxygen engines using fuel with a high boiling point.

The RD–119 engine consists of a combustion chamber with burner head and profile nozzle, turbo-pump aggregate with centrifugal pumps for oxidizer and fuel (one each) and a single component gas generator operating on the main fuel that undergoes thermal dissociation, complete with automation aggregates which include thrust regulators to control fuel to oxidizer ratio, a system of steering nozzles with a gas distributor and a power frame carrying auxiliary aggregates also used for docking the engine with the rocket.

Titanium and other modern structural materials were widely used in the engine construction.

The internal diameter of the combustion chamber is 210 mm and the throat diameter of the nozzle 93 mm. The steering system of the engine is designed for the control and orientation of the second stage of the rocket *Cosmos* in flight. Control is accomplished by the redistribution of gases produced in the turbine between the stationary steering nozzles.

Starting of the engine, control of operation and stopping are carried out automatically on command from aboard the rocket. Ignition is achieved by a pyrotechnical device which provides a reliable, automatically controlled operation depending on altitude conditions. The initial rotation of the turbine with the pumps is carried out by a cartridge placed in the gas generator. Thrust in flight is regulated by varying the flow of fuel fed to the gas generator.

The rocket engines which were developed in subsequent years, for instance, the powerful engines of the launcher rocket *Proton*, have even higher figures of thrust, specific impulse, chamber pressure, degree of expansion in nozzles and specific weight of engine than those of RD–107, RD–108 and RD–119. The significant pressure in the engine system and provision of high-degree complete combustion, as also the realization of a uniform flow of the products of combustion in equilibrium through nozzle with a high degree of expansion, have made it possible to build small-sized powerful engines with exceptionally good characteristics.

The building of high-quality rocket engines operating on efficient propellant is the main business of rocket energetics.

Space flight requires a huge consumption rate of propellant. In designing a rocket the problem arises of making it structurally as light as possible so that a large part of the weight can be assigned to the propellant.

We will show with one more example, what gives the struggle to build highly efficient liquid-propellant rockets with minimum structural weight such importance in the development of astronautics. Let us return to the rocket in the example considered earlier and assume that it became possible to reduce the structural weight from 20% to 5%, reserving not 80% but 95% of the weight of the rocket (without payload) for the propellant. With such structural sophistication the rocket lifts a load not of 1 ton but of 16 tons even using low-quality propellant ($W = 2{,}000$ m/sec). With high-quality propellant ($W = 4{,}000$ m/sec) the magnitude of the payload reaches 41 tons. With such high-quality propellant and structural perfection the single-stage rocket considered above can put a payload of 5 tons into orbit as an earth satellite and can reach the moon with a load of 1 ton.

Let us draw some conclusions. A rocket of heavy structure using satisfactory propellant can fly only 1,000 km. A rocket of great structural perfection and high-grade propellant can fly with the same payload to the

moon or travel the same distance carrying 40 times more load.

The simple examples given above show the basic tasks of space rocket building: the use of the most efficient sources of energy and perfection of the engine and rocket structure.

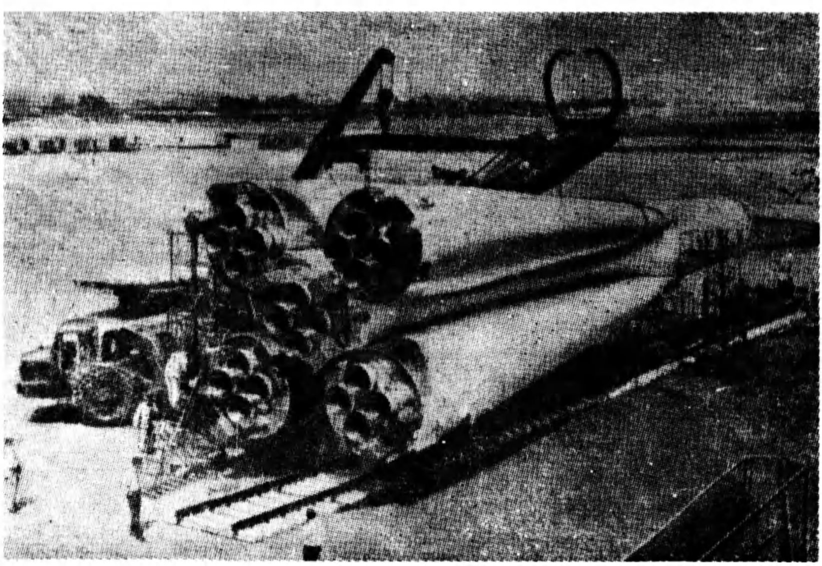
The success achieved by Soviet scientists and designers in the development of rocket energetics laid the foundation for the outstanding triumphs of our people in mastering space.

Rocket trains

"As a result of further creative work by Soviet scientists, designers, engineers and workers a multi-stage rocket has now been built whose last stage is capable of attaining the escape velocity of 11.2 km/sec, providing the possibility of interplanetary flights." This was part of the Tass report on the launching of the first space rocket in the world. And subsequently on every new achievement in the field of space exploration we read again and again: "The launching was carried out with the help of a multi-stage rocket."

What, indeed, are modern multi-stage rockets? Why did the necessity arise to use for space flights rockets consisting of a large number of stages? What technical effect is achieved by increasing the number of rocket stages?

Let us look at the result of using a large number of stages in rockets. Let us study a space rocket that must take an automatic station with a mass



Soviet launcher rocket *Vostok*. The power plant in the first stage consists of four-chamber RD–107 engines.

of 1 ton beyond the region of the earth's activity and put it into a heliocentric orbit. Let us assume that the structural perfection of the rocket is such that for each of its stages the mass of the propellant is 90% of the total mass while the structure accounts for the remaining 10%. Let the exit velocity of the gas be 3,000 m/sec. A single-stage rocket with these parameters cannot manage the task. Accounting for the energy necessary to overcome air resistance the propellant stocks on board would have exceeded the mass of the rocket itself by 58 times. Building such a rocket structure is not within the reach of modern engineering science. By using a rocket consisting of two stages it is possible to solve this problem.

But the mass of a two-stage rocket becomes 848 tons (including 763 tons of propellant). This means that a payload of little more than one thousandth of the overall mass of the rocket can be put into the orbit around the sun. A three-stage rocket designed for the same purpose will have a mass of 185 tons. By increasing the number of stages to four it is possible to reduce the mass of the rocket to 140 tons. A five-stage rocket will have a mass of 124 tons, and a six-stage one 116 tons.

In the last case the quantity of propellant required is little more than 100 tons, i.e. 7.5 times less than that in the two-stage variant. The calculations, of course, are quite approximate. Increasing the number of stages increases the weight of decoupling mechanisms. It is more difficult to make a small-sized stage with the same degree of structural perfection as a large stage and during the launching of heavier rockets smaller losses of velocity due to the action of aerodynamic and gravitational forces are expected. But the figures indicated show quite clearly the overall correlation.

In judging the effectiveness of increasing the number of stages certain regularities deserve notice. Firstly, it is clear that with the increasing number of stages the mass required of the rocket decreases very rapidly in the beginning, but later becomes less significant. Therefore, considering that every new stage complicates the construction of the rocket, it is advisable to increase the number of stages only to the extent that it contributes a significant reduction in the launch weight. Secondly, one must note that increasing the number of stages has the maximum effect only when a substantial fraction of the stage mass is accounted for by the structure. This is quite clear. The heavier the construction, the more empty sections of the rocket body can be profitably jettisoned.

To launch artificial satellites of the earth multi-stage rockets are used. Let us consider a four-stage rocket with a launch weight of 100 tons as an example illustrating the importance of the struggle to reduce the structural weight. In each stage assume 80% of the mass is accounted for by the propellant and 20% by the structure. We will assume that the exit velocity of gas is 2,000 m/sec. Such a rocket will be able to put a satellite weighing 50 kg into orbit at an altitude of 200 km. If perfect construction of the

rocket increases the propellant storage to 95% of the weight of each stage the rocket can put into orbit a satellite weighing 650 kg. And if, besides this a more efficient propellant is used (with an exit velocity of 4,000 m/sec) then a four-stage rocket with a launch weight of 100 tons will be able to put into orbit a satellite weighing 5 tons.

One may also note that with the perfection of rocket engines and the use of still more effective propellant or, in other words, by increasing the exit velocity of gases, the launch weight of the rocket can be reduced even with the same (unchanged) degree of structural perfection. Correspondingly, the required number of stages can also be decreased. For instance, if the engine with an exit velocity of gas equaling 2,400 m/sec were to be used on the space rocket considered above and to convey the escape velocity to an automatic station of 1 ton mass, then even in a six-stage variant it would have a launch weight of nearly 400 tons. On increasing the exit velocity by 300 m/sec the required propellant storage would be reduced by almost half and the launch weight of the six-stage rocket would be reduced to 200 tons. A further increase in the exit velocity by 300 m/sec would allow a decrease in propellant storage again by almost half, thus reducing the launch weight to 116 tons.

The figures cited convincingly establish the importance of work on the perfection of rocket engines, of the role of rocket energetics in the development of astronautics.

The success gained by scientists and constructors in developing rocket energetics and in building modern multi-stage rockets is a genuine miracle of engineering art which is responsible for outstanding triumphs in the mastery of space and for opening up new ways to other plants of the solar system for mankind.

We have described the basic problems that the designers must solve in building space rockets and attempted to set out basic information about the construction of rockets. Now it will be interesting to illustrate this information with an account of the actual construction of certain rockets to give some idea of the modern level of rocket building. As an example of modern heavy rockets let us take the rocket *Saturn-V* described in detail in technical literature. This

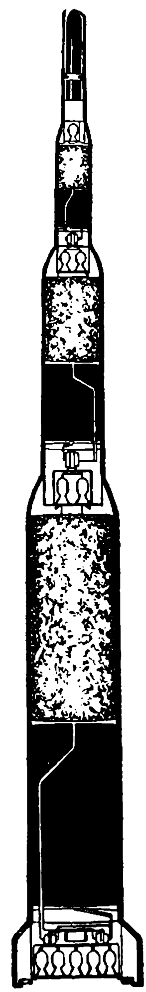


Diagram of a four-stage rocket. Distribution of weight: payload—10 tons, structural weight—90 tons, weight of the propellant—900 tons. The velocity at the end of operation of the engines of the first stage—2.5 km/sec, second stage—6.4 km/sec, third stage—10.0 km/sec, fourth stage—12.9 km/sec.

rocket has put an artificial earth satellite weighing more than 100 tons into circular orbit at an altitude of nearly 200 km and an apparatus weighing up to 45 tons on a flight trajectory toward the moon. The rocket *Saturn–V* is of interest because it lofted the spaceships *Apollo–11* and *Apollo–12* on which astronauts performed the first flights to the moon.

Saturn–V is a three-stage rocket. The rocket S–1C is used as the first stage. The main components of the rocket are: fuel tank, oxidizer tank and engine compartment. Between the tanks there is an adapter. The rocket S–1C is connected with the second stage of the launcher rocket with the help of the adapter.

The fuel tank has the shape of a cylinder with hemispherical end-plates. Length of the tank is 13.1 m with a maximum of 658 tons (in practice during flights the tank contains nearly 600 tons of fuel). Five pipelines with a diameter of 51 cm pass through the fuel tank to bring liquid oxygen to the engines. The pipelines are enclosed in a tunnel 56 cm in diameter. The fuel from the tank is delivered to the engines through 10 pipelines. The fuel tank is pressurized with gaseous helium. The helium is preserved in liquid form under high pressure (210 atm) in four cylindrical balloons mounted in the oxidizer tank.

The oxidizer tank also has the shape of a cylinder with hemispherical end-plates. Length of the tank is 19.5 m and maximum capacity 1,515 tons (in practice the tank is filled with nearly 1,400 tons of liquid oxygen during flight). The oxidizer tank is pressurized with oxygen which is initially vaporized in a heat exchanger and enters the tank through a hole in the upper end-plate.

On the first stage of the launcher rocket *Saturn–V* five F–1 rocket engines working on hydrocarbon fuel RP–1 and liquid oxygen are mounted. One engine is rigidly fixed along the axis of the rocket and the remaining ones are mounted on hinges along the periphery. In the neutral position the axes of the peripheral engines are parallel to the rocket's longitudinal axis. These engines can be swiveled through an angle of $\pm 7°$ in two planes.

The engine F–1 has the following characteristics: thrust—690 tons, weight—9 tons, length—5.8 m, combustion chamber diameter—1 m, diameter of the nozzle exit section—3.66 m, degree of expansion in nozzle—16, weight of turbo-pump aggregate—1,270 kg, length—1.52 m, diameter—1.22 m, power of the turbine—60,000 hp, discharge of the fuel pump—0.9 tons/sec, that of the oxidizer pump—1.8 tons/sec.

The combustion chamber and the nozzle are made of steel tubes set in two layers. To cool the tubes the fuel flows through the tubes forming the inner layer to the section of the cooled part of the nozzle and thereafter through the tubes of the outer layer and through 32 radial channels to the injector head with 3,700 burners. The diverging portion of the nozzle is uncooled.

The S–2 rocket is used as the second stage of launcher rocket *Saturn-V*. The compartment for tanks contains a liquid hydrogen tank of 1,080 liters capacity and a liquid oxygen tank of 350 liters capacity separated from the former by a partition. The outer surface of the tanks is coated with a layer of thermal insulator which is covered by a layer of nylon and heat resistant film. There are five J–2 rocket engines mounted on the rocket S–2.

At the third stage on the launcher rocket *Saturn–V* the S–4B rocket is used. Its tank compartment is a 6.7 m long cylinder with hemispherical end-plates. It is divided by a hemispherical partition into fuel tank (front end) and oxidizer tank. The partition is a twin-walled construction made of aluminum alloy. The space between the walls is filled with honeycomb fiberglass material. The fuel tank is lined with thermal insulator.

For pressurization of the fuel tank, gaseous hydrogen collected from the cooling jacket of the engine is used. For pressurization of the oxidizer tank gaseous helium preserved in eight titanium alloy balloons located in the fuel tank is used. Before entering the oxidizer tank the helium is made to pass through a heat exchanger mounted on the engine. A boost (supercharging) pressure of 2–3 kg/cm^2 is maintained in the tanks.

To build pressure in the tanks at the time of repeated firing of the engine 10 balloons with uncooled helium mounted on the engine frame are used.

The main characteristics of the launcher rocket *Saturn–V* and its stages are as follows:

Parameter	Rocket as a whole	First stage	Second stage	Third stage	Equipment compartment
Height, m	85.8	42.06	24.84	17.91	0.91
Diameter of the body, m	10.06	10.06	10.06	6.58	6.58
Weight, tons	2,707	2,126	465	114.3	1.80
Weight of propellant, tons	2,527.5	1,995.8	427.3	104.35	—
% weight of propellant in stages	—	94%	92%	91%	—
Propellant	—	RP–1 + O_2	H_2+O_2	H_2+O_2	
Engine unit-rocket engine	—	Five F–1	Five J–2	One J–2	
Thrust of engine unit, tons	—	3,450	510	102	
Operational duration, sec	—	150	390	480	

The J–2 liquid-propellant rocket engine is used as the main engine in the S–4B rockets. In addition two blocks of five auxiliary engines are mounted

on it. The larger among them, with a thrust of 800 kg, is fired to accelerate the rocket before the first and second firings of the main engine, and the smaller ones are used to accelerate the rocket before liquid hydrogen vapors are released during flight in geocentric orbit.

In the USA *Atlas–Ajena* launcher rockets have been widely used for launching artificial earth satellites and automatic stations for investigation of the moon and planets. With the help of this rocket about 100 satellites were put into orbit. These are communication satellites, satellite-observatories and reconnaissance satellites. The *Atlas–Ajena* placed the space vehicles *Ranger* and *Lunar Orbiter* on the flight path to the moon and the *Mariner* on an interplanetary course.

The cost of manufacturing and launching one *Atlas–Ajena* rocket is $ 8 million.

The *Atlas–Ajena* rocket can put a payload weighing up to 2.7 tons into geocentric orbit at an altitude of 550 km or impart escape velocity to payloads weighing up to 430 kg. The launch weight of the rocket without payload is 125.5 tons, the height is nearly 30 m and the maximum diameter of the body is 3.05 m.

As the first stage on the launcher rocket *Atlas–Ajena* different versions of the rocket *Atlas* are used, both the ballistic variant and those specially built for use as launcher rockets.

Basic characteristics of the *Atlas* rocket

Height, m	22.86
Diameter body, m	3.05
Diameter starting engines' cowl, m	4.90
Weight, tons	118
Weight propellant, tons	112
Propellant	RP-1 + liquid oxygen
Thrust, tons:	
of starter engines	$2 \times 74.8 = 149.6$
of main engines	25.9
of steering engines	$2 \times 0.45 = 0.9$
Specific thrust, kg·sec/kg	255
Operational duration, sec:	
of starting engines	145
of main engine	300
of return engines	360

On these rockets carrier tanks of monocoque construction made of steel sheets are used. The tank compartment is 18 m long and is divided by an internal partition into an oxidizer tank (70,875 liters capacity) and a fuel

tank (43,665 liters capacity). While storing or transporting the rocket an excess pressure of about 0.7 kg/cm^2 is maintained in the empty tanks.

The engine units of the *Atlas* rockets consist of a main engine, two starting and two steering engines. All the engines start operating simultaneously. After about 2.5 minutes of flight the starting engines are jettisoned.

The combustion chambers of the starting and main engines are mounted on hinged suspensions and provided with hydraulic drives which swivel them for flight control. The steering engines are fixed on hinged suspensions on the sides of the tank compartment and are covered with cowls.

The propellant feed system is turbo-pump. The turbine of the turbopump aggregate is started with the help of a cartridge-pressure accumulator and later operates on the gas generator, using basic components of the propellant (with excess fuel).

As the second stage of the *Atlas–Ajena* launcher rockets *Ajena* rockets are used. These are joined to the upper part of the *Atlas* rocket with the help of a special adapter. During the separation of stages explosive bolts and two brake solid propellant rocket engines mounted on the adapter come into operation and jettison the adapter with the first stage. Meantime the second stage rolls off the adapter along the guide provided.

Basic characteristics of the *Ajena D* rocket

Height, m	7.62
Maximum diameter, m	1.525
Weight structural, kg	770
Weight propellant, kg	6,150
Fuel	Asymmetrical dimethyl-hydrazine
Oxidizer	Red fuming nitric acid
Engine unit	One liquid-propellant rocket engine
Thrust, kg	7,250
Oxidizer-to-fuel ratio	2.55
Maximum operational duration, sec	243

Light cast magnesium alloy is used in the construction of the *Ajena* rocket. The tank compartment is divided into two sections: in the lower section there is oxidizer and in the upper section fuel. The pipeline through which fuel is fed to the engine passes through the oxidizer tank. For pressurization of the propellant compressed helium is used.

The engine unit of the *Ajena D* rocket has no casing, simplifying access to the aggregates located in it. In the compartment space is provided to mount part of the payload, which is fixed to the body.

Until the separation of the starting engines of the first stage occurs the rocket is controlled by an autopilot placed aboard it. After separation of the starting engines and until separation of stages it is controlled by command from earth. After the separation of the first stage the orientation of the *Ajena D* rocket in the active phases of flight is ensured by hinged engines (pitch and yaw) and control jet nozzles (bank). In the passive phases of flight it is controlled in all directions by control jets.

Spaceship flight control

In describing the flight of the spaceship *Voskhod* its Commander, Pilot-Astronaut V.M. Komarov, said: "My assignment included controlling the ship. This was necessary so as to observe a certain phenomenon that was of interest to us in the best possible manner. I maneuvered the ship several times. We tested the orientation system in flight."

All other spaceships are also made maneuverable. Why is it necessary to maneuver a spaceship flying along a set orbit? What is the technique of controlling a spaceship in space?

The control systems of spaceships are entrusted with responsible assignments. The first of them is the stabilization of the spaceship and its orientation in space.

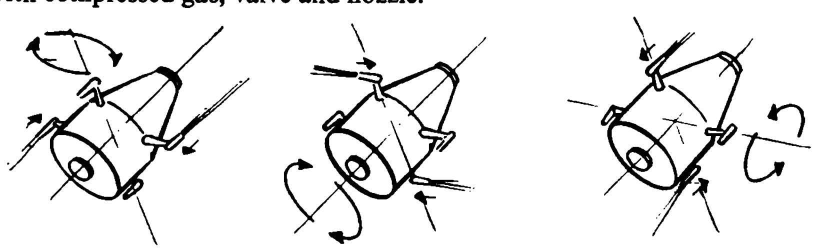
Every space vehicle, after the engine has stopped, flies along a perfectly set orbit that totally depends on the magnitude and direction of the velocity gained at the end of the active phase of the flight. The vehicle will not leave the orbit unless acted upon by a new impulse of force. To continue its flight along this orbit it needs no engine. But while moving along the orbit a space vehicle of any type does not maintain its attitude in space. It arbitrarily rotates about its center of mass. The reason for this instability on the part of a spaceship can be the disturbing influence of light pressure, such as the earth's magnetic field, on the conducting parts of the spaceship, shocks from micrometeorites and many other factors.

By what technical means is it possible to carry out the required orientation of the spaceship? One is small steering rocket engines.

These engines are attached in pairs to the sides of the ships casing at diametrically opposite points. Their nozzles are directed along the axis of the spaceship but in opposite directions. If the engines are fired one by one on each side through the nozzles mounted in opposite directions the spaceship will begin to turn slowly about the vertical axis. Let us shut off these engines and give gas to the other two. The ship will begin to rotate about the same axis but in the opposite direction. Let us mount two more pairs of engines, one at the top of the ship and the other at the bottom. The astronaut can then rotate the spaceship at will about the lateral axis either lifting its nose upward or lowering it downward. For the astronaut to be able to turn his ship about the longitudinal axis it is necessary to mount two

more pairs of engines on the sides of the body with nozzles directed downward and upward. Thus with the help of steering engines it is possible to turn the spaceship about any of its three axes.

Small-sized engines are used for this purpose. An extremely small consumption of propellant, measurable in milligrams per second, is needed for their operation. At the same time the steering engines have to be reliable, capable of repeated firings and operating for a long duration. For their operation the use of high-grade fuels and oxidizers is, therefore, not always rational. In a number of cases it appears to be more rational to simply use some compressed gas, like nitrogen. If cold but highly compressed nitrogen is fed to the nozzle it expands while flowing through it and acquires a velocity of several meters per second. This velocity will, of course, be 4–6 times less than the exit velocity of the products of combustion from the nozzle of the rocket engine. And, indeed, it is often necessary to increase its flow compared to that of the liquid propellant. But the simplicity and reliability of the construction can justify this drawback since the overall flow of gas through the steering engines throughout the duration of the flight, particularly when it lasts only a few days, is small. Such steering engines are sometimes called steering nozzles since the whole unit consists of a bottle with compressed gas, valve and nozzle.



Control of space vehicle with the help of steering engines. Three pairs of steering engines make it possible to turn the vehicle about any of its three axes.

Controlling the attitude of the spaceship is possible with the help of flywheels. The idea of this kind of control was put forward by K.E. Tsiolkovskii himself. The principle of operation of this control system is as follows:

Aboard the spaceship a flywheel is mounted on an axle fixed to the body and passing through the center of mass of the whole system. If the flywheel is rotated with some angular velocity the spaceship will begin to rotate in the opposite direction. Since the flywheel is small, as compared with the considerable mass of the spaceship, the velocities of rotation are different. According to the law of mechanics the product of the magnitudes of the moments of inertia of the flywheel and that of its absolute angular velocity, i.e. the moment of momentum of the flywheel, are equal to that of the spaceship. This means that by rotating a small flywheel at a large velocity it

is possible to turn the heavy space vehicle slowly about the same axis in the opposite direction.

After the spaceship is turned through the required angle the flywheel is stopped, thereby also stopping the rotation of the spaceship. If the spaceship has by this time acquired a significant rotational velocity the flywheel is run for some time in the opposite direction, which decelerates this rotation.

The control systems of the spaceships described can be used both in automatic control regimes, in which the ship's attitude is observed by instrument, and in manual control by the astronaut himself. In using a flywheel the astronaut can rotate it himself with his muscular force and turn the spaceship without spending any of the fuel aboard.

Very often, particularly on interplanetary flights, the problem is not of turning the spaceship but of maintaining its orientation unchanged, i.e. to stabilize the spaceship's attitude. Hence the name "spaceship stabilization system."

It can easily be seen that the systems described above can solve both problems. They can turn the space vehicle about any of its axes according to the pilot's will and stop its rotation if it is caused by certain external forces or by the movement of the astronauts in the cabin.

A reliable stabilization system needs highly accurate and smoothly operating automatic equipment. This equipment must attentively observe the spaceship's attitude, holding it strictly according to the flight program.

The stabilization of spaceships is a highly complicated and responsible task. The flights of the Soviet spaceships *Vostok, Voskhod* and *Soyuz* have shown that our engineering science has successfully solved the problem.

The control of a spaceship is not confined to the problems of stabilization and attitude. Problems such as correcting the interplanetary (flight) course or changing the orbit that the ship is following also arise. It is known that the average distance between the orbits of the earth and Mars is more than 70 million km. But the spaceship cannot travel even this distance in a straight line. It will travel along a convex elliptical route gradually moving away from the orbit of the earth and approaching that of Mars. It will have to traverse many hundreds of millions of kilometers. With such a long route even the most negligible error in either magnitude or direction of velocity is sufficient for a ship to miss Mars or pass it by at a distance of hundreds of thousands, if not millions, of kilometers.

Not only during flights to the distant space of the solar system but also during movement of an earth satellite along an orbit it is extremely important to have a provision for changing course so that the pilot can at will lift the satellite-spaceship to a higher orbit, change the direction of the flight or reduce altitude. Besides such general maneuvering, it is necessary on every flight to transfer the spaceship from its orbit to an approach path in order

to land on the earth's surface. How is this done? How are the altitude, speed and direction of flight of a spaceship in space changed?

Such problems can be solved only with the help of rocket engines. Here rotating flywheels will not help. The motion of the center of mass of the spaceship can never be changed by internal forces. In order to give the spaceship additional velocity it is necessary to fire rocket engines and spend the corresponding amount of propellant.

The question remains as to how much propellant needs to be spent so as to vary the velocity of a ship, say, by 1 m/sec or 100 m/sec. The well known Tsiolkovskii formula answers this question. The amount of propellant required to be spent to increase or decrease the velocity of the spaceship by 100 m/sec is equal to 4% of the total weight of the ship. To increase the velocity by 1 km/sec the required amount of propellant would be 20–40% of the total weight of the ship. Here the amount of propellant depends also on the exit velocity of the gas. If, in addition, the weight of the propellant tanks and other structural elements of the power plant is taken into account the amount needed to change the velocity of the spaceship will increase still further. Change of flight velocity in space is a costly affair.

The problem of changing the altitude of the orbit or the direction of flight is the same as that of giving additional velocity to the spaceship.

Change in altitude as a function of increase in velocity can be determined by an approximate formula

$$\Delta H \approx 3.5 \Delta V,$$

where ΔH is the change in the orbital altitude, km; ΔV is the increase in velocity, m/sec.

Consequently if the velocity of a satellite-spaceship is increased by 1 m/sec the altitude of the orbit at the opposite point increases by 3.5 km. And to lift the whole orbit by 3.5 km it is necessary to increase the velocity of the spaceship twice, each time by 1 m/sec. This formula holds good only for spaceships flying along Gagarin's orbit, i.e. along the orbit located at altitudes from 160 to 400 km.

Soviet science took to building spaceships capable of carrying out numerous maneuvers. It was in 1963 and 1964 that the vehicles *Polet-1* and *Polet-2* were launched. They executed maneuvers in various directions, changing the altitude of the orbit and its plane. Successful tests of the *Polet* vehicles were important steps on the way to spaceships capable of maneuvering within wide limits.

Scientists are investigating various methods of increasing the maneuverability of spaceships. Here a boundless field for creative invention is open.

What has been achieved is not the limit but only a beginning. Let us imagine that the time has come to build gigantic interplanetary spaceships for flight to Mars and Venus. They will make trips lasting many months.

Which of the stabilization systems described should we choose for them? The system with flywheels? But to control huge spaceships heavy flywheels are needed. This is not acceptable in interplanetary technique. The system of steering engines operating on compressed nitrogen? But during a long flight they spend an excessively large amount of gas. Even the most economical liquid-propellant rocket engines will require a very large quantity of propellant. This means that one must think of investigating and building a new, incomparably more effective, stabilization system for interplanetary spaceships. And moreover start thinking about it right now so as to be able to research and work out the necessary systems in time.

To show how many-sided the problem of controlling spaceships is we will describe a very interesting idea. In the distant future this idea may be put into practice.

During flights to the near planets it is possible to use solar rays to control the ship. For this it is necessary to mount a solar sail on the ship. Since light pressure is very small the sail must be of a very large size. By changing the position of the sail it will be possible to vary the magnitude and direction of the light pressure force and thus control the ship's flight.

Today, of course, in the days of the first outstanding flights of spaceships, it cannot yet be decided which control system will appear to be the most rational in the future. But one can predict with confidence that scientific expeditions will fly aboard reliably controlled spaceships to the orbits of Mars and Venus and later to the other planets of the solar system.

SPACESHIP VOSTOK

Yuri Alekseevich Gagarin, the first pilot-cosmonaut in the world, opened the way to cosmic space for the whole of humanity. He performed his heroic flight on the spaceship *Vostok* which was put into orbit by a three-stage launcher rocket. Creation of this rocket was a genuine triumph of Soviet science and engineering. Today, when space-rocket technology has entered the era of rapid development, many new perfected orbital spaceships and launcher rockets of different types are being created. In future the inspired thinking of scientists and the creative labor of workers will build even more sophisticated space vehicles. But however outstanding these vehicles may be in the creation of a space rocket system for the world the *Vostok* of S.P. Korolev's design will go down in the history of the technique of space conquest as a notable achievement.

The launcher rocket *Vostok* is very interesting from the point of view of layout and structure. It has three stages. The first and second stages were made according to the so-called "package" scheme, i.e. with longitudinal split-up, while the third stage was attached to the second in series, i.e. with

lateral split-up. On the third stage the spaceship *Vostok* was mounted shielded by a head cowling to protect it from aerodynamic loading during flight in the dense layers of the atmosphere.

The total length of the launcher rocket *Vostok* was 38 m and the diameter (with air vanes) 10.3 m. The rocket placed in orbit a payload weighing 4,725 kg, the spaceship *Vostok*.

The first stage of this rocket consists of four identical blocks 19 m long and 3 m in diameter (maximum) located around a central block having a length of 28 m and a diameter of 2.95 m and acting as the second stage. These stages are connected with two belts of structural attachments which have a mechanism for separating the side blocks from the central one after the first-stage engines have finished operating.

Each of the four blocks of the first stage of the launcher rocket *Vostok* has an independent engine unit. On these blocks are mounted the liquid-propellant RD–107 rocket engines, one on each block. The total thrust of the engines of all four blocks of the first stage is 408 tons (in vacuum). They spend 1.3 tons of propellant per second.

On the second stage, i.e. in the central block, an RD–108 engine of 96 tons thrust is mounted. The third stage has a diameter of 2.58 m. Its length together with the spaceship and cowling is 10 m. A single-chamber rocket engine with four steering nozzles is mounted on it.

At the start, all the engines of the first and second stages were fired to operate simultaneously during the active phase of the flight of the first stage. Due to the joint working of the power units of the two stages the total thrust of the rocket *Vostok* in the initial phase of the flight reached 500 tons. The joint operation of the five rocket engines continued until the propellant in the side blocks was exhausted and the engines shut off. After this the side blocks were jettisoned and the rocket, freed from the empty blocks of the first stage, continued its flight with the rocket engine of the second stage operating in the regime of total thrust.

After the rocket emerged from the dense layers of the atmosphere the head cowling was thrown off so as to facilitate further climb and gain greater speed by jettisoning a load that had become redundant.

The second stage engine operated until the propellant of the central block had been used up. The duration of operation was about 2.5 times more than that of the first-stage engines.

After this was shut off the rocket flew for some time with its engine inoperative. Later the firing of the third-stage rocket engine and its separation from the central block took place.

The third stage put the spaceship into the prescribed orbit. When the rocket reached the estimated velocity the control system gave the command to shut off engines and separated the spaceship from the launcher rocket.

Before human orbital flight was realized the rocket *Vostok* and its

systems underwent numerous ground tests and flight tests which ensured high reliability of all systems of the rocket and high accuracy for the orbiting of a spaceship.

Every new model of launcher rocket arriving at the Baikanur cosmodrome undergoes in advance the integrated tests of engines, control systems and all equipment that guarantee a reliable launch and flight. On the cosmodrome the launcher rocket is again put through careful trials. After this the final assembly of its blocks takes place and it is mounted on the launching pad. From this time to the moment of take-off the functioning of all systems of the rocket is continuously monitored with the help of remote automatic ground equipment. Aboard the rocket there is an interlocking system which automatically shuts off the engines in the event of malfunction of any system in the rocket. Special airborne and ground devices determine the moment of climb of the rocket and monitor the condition of its systems throughout the flight.

Thanks to its good energy characteristics and the high reliability of the launcher rockets the *Vostok* guaranteed careful handling of satellite-spaceships and successful orbiting of the world's first spaceship around the earth.

The spaceship *Vostok* consists of a re-entry capsule and instrument compartment connected with each other by four tension strips.

The weight of the spaceship together with the last stage of the launcher rocket is 6.17 tons and 4.73 tons without it. The length of the ship with the last stage is 7.35 m. The diameter of the re-entry capsule in which the astronaut's cabin is situated is 2.3 m with a weight of 2.4 tons.

The re-entry capsule is covered with a layer of thermal shielding to protect it from high temperatures on descent. It has three hatchways: a parachute hatchway, a technological hatchway and a bail-out hatchway, and also three windows with heat-resistant glass. One of the windows is provided with an optical device or "look" essential for orientation of the spaceship in space during manual control. Inside the spaceship there are a number of systems and instruments controlling the life support systems and registering the parameters of the medium in the cabin. The astronaut in his spacesuit sits in an ejector seat. The systems and instruments are so located that in any position of the astronaut's body—fixed or floating freely in the cabin—they are readily accessible. The location of the seat is chosen for minimum load on the astronaut. In the body of the seat the system of spacesuit ventilation, ejector device, parachute system and ground accident reserve (food, water, radio communication) are mounted.

The seat also serves as a rescue device during launching in case of accident or the need arising to evacuate the astronaut. Apart from the ejector device special rocket engines can move the astronaut away from the danger zone and lift him to an altitude sufficient for reliable operation of a parachute rescue system.

The overall weight of the equipment mounted in the re-entry capsule is 800 kg.

The airconditioning system guarantees normal humidity, concentration of oxygen, pressure (nearly 750 mm) and temperature within the range 12–25°C. Stocks of food, water and chemical substances for regeneration of air are carried for an estimated 10 days.

The orientation system works either automatically or manually. It includes gyroscopic and optical pick-ups, computer devices and micro-rocket engines. The engines of the orientation system and the stock of working medium for them (compressed air) are accommodated on the outer surface of the spaceship.

The descent of the ship takes place at an accurately pre-set time and in a predetermined region. After receiving the command to descend, the automatic orientation system fixes the position of the ship in space with the help of the pick-up. Then the brake engine unit that moves the ship into a descending trajectory is fired. The orientation can be carried out manually. After the operation of the brake engine unit is completed the descending capsule separates from the instrument compartment which is destroyed in the dense layers of the atmosphere.

During the return of the re-entry capsule the temperature of the boundary layer of air reaches 10,000°C and aerodynamic resistance increases to 20 tons which is equal to about eight times the loading.

The astronaut can land either in the capsule or separately. In the latter case the lid of the access hatch is fired off, while at an altitude of about 7,000 m, the seat with the astronaut is ejected two seconds afterward and the pilot's parachute system goes into action. At an altitude of 4,000 m the seat is separated and falls freely. The astronaut continues to descend on the parachute.

Accident reserve and a boat suspended by a wire rope about 15 m long descend with him. The boat can be automatically filled with air to guarantee rescue in case of a water landing. The astronaut's landing velocity is nearly 6 m/sec. The antenna is automatically put into operation and a direction finding radio signal is switched on.

Simultaneously with the astronaut's landing system the parachute landing system of the re-entry capsule also starts operating at an altitude of 4,000 m.

The creation of the *Vostok* space-rocket system is an outstanding achievement of Soviet and world rocket and space technique. The fruitful application of launcher rockets in astronautics over several years and the historical achievement in learning about and mastering outer space attained by Soviet science with their help make the rocket and the spaceship *Vostok* one of the most remarkable accomplishments of the engineering thinking of the 20th century.